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STUDIES OF THE LATERAL-DIRECTIONAL FLYING QUALITIES OF A TANDEM HELICOPTER IN FORWARD FLIGHT

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SUMMARY

An investigation of the lateral-directional flying qualities of a tandem-rotor helicopter in forward flight was undertaken to determine desirable goals for helicopter lateral-directional flying qualities and possible methods of achieving these goals in the tandem-rotor helicopter. On the basis of comparisons between flight measurements for various configurations and corresponding pilots' opinions, it is concluded that some important considerations are: the presence of pedal-fixed directional stability, no reversal in rolling velocity during a turn following a lateral step displacement of the control stick with pedals fixed, and reasonably well damped lateral-directional oscillations. These conclusions are also expressed in the form of desirable flying-qualities goals.

Comparison between directional stability as measured in flight and rotor-off model tests in a wind tunnel shows qualitative agreement and, hence, indicates such wind-tunnel tests, despite the absence of the rotors, to be one effective method of studying means of improving the directional stability of the tandem helicopter.

Flight-test measurements of turns and oscillations, in conjunction with analytical studies, suggest possible practical methods of achieving the goals of satisfactory turn and oscillatory characteristics in the tandem helicopter.

INTRODUCTION

For the past few years the National Advisory Committee for Aeronautics has been studying the flying qualities of helicopters in order to set up flying-qualities criteria and to provide means of improvement. The initial flying-qualities work was mainly concerned with single-rotor helicopters. Although the lateral-directional flying qualities of single-rotor helicopters in contact flight were considered generally satisfactory, familiarization flights by NACA pilots in tandem-rotor helicopters indicated the need of studying this type of helicopter.

In this paper lateral-directional flying-qualities studies of a tandem helicopter in forward flight are reported. These studies, experience with single-rotor helicopters, and studies made of airplanes such as those reported in reference 1 provide a basis for lateral-directional flying-qualities goals applicable to the tandem helicopter as well as to all other types of helicopters. In addition, these flight results, supplemented by analytical studies, provide a basis for improvement of the tandem type of helicopter in order to achieve these goals.

It should be pointed out that further work covering different flight conditions may indicate additional goals to be desirable.

All the various configurations of the test helicopter were flown by two NACA test pilots experienced in flying-qualities studies who agreed on all important points.

As in discussions of airplane stability, the word lateral will hereinafter be applied to combined lateral-directional motions.

TEST EQUIPMENT

The test tandem helicopter is shown in figure 1 and its principal dimensions and approximate physical characteristics are listed in table I. Figure 1(a) is a side view of the entire helicopter, whereas figure 1(b) is a closeup of the empennage. The helicopter has conventional pilot controls: stick, pedals, and collective-pitch lever. Longitudinal control is achieved by longitudinal motion of the stick which produces a combination of longitudinal cyclic pitch and differential collective pitch, the latter providing by far the larger pitching moment. Rolling control is achieved by lateral motion of the stick which causes lateral cyclic-pitch change of both rotors. Directional control is achieved by use of the pedals which causes differential lateral cyclic-pitch change. Movement of the collective-pitch lever changes the collective pitch of both rotors.

Calibrations of lateral cyclic pitch of the two rotors produced by lateral stick motion and rudder-pedal deflection are presented in figure 2. As can be seen from the figure, unequal lateral-cyclic-pitch changes are produced in the two rotors by lateral stick motion. The effect of this inequality in producing yawing moments is discussed subsequently.

The helicopter was equipped with standard NACA recording instruments with synchronized time scales which measure airspeed, angular velocities about the three principal inertia axes, pilot control positions, sideslip angle, and normal and lateral accelerations at the pilots' seats.

In order to aid the pilots in performing the desired maneuvers, preloaded spring devices were installed on the pedals and in the lateral control mechanism of the stick during the later part of the test program. These devices helped the pilot to hold the controls at any desired position.

LATERAL-DIRECTIONAL FLYING QUALITIES OF TEST HELICOPTER

The pilots reported three main lateral-directional flying-qualities difficulties for the original configuration in forward flight: The helicopter exhibited pedal-fixed directional instability at low power and in autorotation, was statically stable directionally but exhibited an unstable lateral oscillation at the higher power settings, and had undesirable maneuver characteristics during turns. During normal flying at all forward flight conditions, the pilots objected to the erratic and out-of-trim control forces; however, this paper deals only with the three flying-qualities problems mentioned previously.

Lateral Stability Characteristics at Low Power and in Autorotation

In this section are presented studies of the lateral stability characteristics of the test helicopter at low power and in autorotation.

Original configuration.- In figure 3 is presented information on control-fixed effective dihedral and directional stability obtained by measuring lateral stick and pedal position during steady sideslips at 70 knots in autorotation. The curve of pedal position in figure 3 for the original configuration indicates a large-magnitude pedal-fixed directional instability in that almost full pedal travel was required to overcome the unstable yawing moments. As would be expected from the results of studies of airplane stability, the pilots considered this characteristic unsatisfactory.

The lateral motions of the stick shown in figure 3 produce some differential lateral cyclic pitch. However, as can be seen from the data presented in figure 2, the differential lateral cyclic pitch produced by the lateral stick motion is small compared with that produced by the pedal motion for the data presented in figure 3. Thus, the pedal motion is a direct measure of the directional stability.

Wind-tunnel tests of a model of the fuselage-empennage of the test helicopter indicate directional instability at positive angles of attack, as in autorotation, in spite of the presence of the vertical fins. Calculations indicate that the rotors produce little yawing moment due to

sideslip. The fuselage is thus indicated to be the main source of the pedal-fixed directional instability.

The fuselage of the tandem helicopter has certain characteristics which tend to aggravate the usual directional instability of a fuselage: It is considerably larger than the fuselage of an airplane of equivalent gross weight and its center of gravity tends to be near the midpoint as compared with the more forward center-of-gravity position of the airplane.

Configuration as modified with spoilers.- This directional instability in autorotation has occasionally been reported as being a problem of inadequate directional control. In order to determine whether the control would be adequate if the helicopter were directionally stable and also to determine whether simple static directional stability would be sufficient for satisfactory lateral stability, it was decided to remove the directional instability by whatever means could be devised.

Wind-tunnel tests indicate that a spoiler placed around the nose of the fuselage will reduce its directional instability. The spoiler probably achieves this result by destroying the negative pressure peak that usually builds up at the nose of a sideslipping fuselage on the side away from the relative wind. Several different spoiler configurations were studied, both in the tunnel and in flight. The most effective configuration, as determined in flight tests, is shown in figure 4. The rearward spoiler shown in the figure actually made only a slight improvement over the effectiveness of the configuration with the forward and underside spoilers alone. The holes and pickets on the front and underside spoilers were for the purpose of achieving a smoother type of separation.

The plot of pedal position in figure 3 for the helicopter as modified with spoilers indicates a substantial amount of directional stability except for a small region near zero sideslip. Inasmuch as the directional instability of the original configuration showed no significant nonlinearities near zero sideslip, the nonlinearity present in the modified configuration is thought to be a fuselage-spoiler flow-separation effect and not a basic tandem-rotor problem.

The pilots reported the flying qualities of the helicopter in autorotation to be much improved by the addition of the spoilers. They would have preferred a further improvement in the region near zero sideslip where the directional stability was about neutral, but they thought that the improvement already achieved was far more valuable than any subsequent improvement could be. Directional control was not considered a problem.

The specific amount of directional stability needed to produce satisfactory flying qualities could not be determined on a simple static

basis; any such minimum amount probably depends, as for airplanes, on the dynamic characteristics of the aircraft.

Dynamic characteristics of helicopter as modified with spoilers in autorotation.- Pilots' observations and instrument records indicate that, if the helicopter with the spoilers on is disturbed laterally in autorotation, a large-amplitude lateral oscillation, mainly in yaw, will quickly build up. The yawing moments which act during such oscillations can, in general, be produced by pedal deflection, lateral stick deflection, yawing velocity, sideslip angle, and rolling velocity. Calculations indicate the tandem helicopter to have only negligible yawing moment due to rolling velocity; a condition which leaves yawing velocity and sideslip angle as the only possible sources of yawing moment during the oscillation, inasmuch as the pedal and lateral stick positions were held fixed. From recorded time histories of the yawing velocity and sideslip angle during such an oscillation, a plot of yawing moment against sideslip angle was obtained. The yawing moment was obtained by taking slopes of the yawing-velocity record and multiplying them by the moment of inertia in yaw. In the region near zero sideslip, the plot showed two values of yawing moment, one for each direction of yawing, for the same value of sideslip. Inasmuch as the yawing velocity to the right was more positive (more moment to right) than the yawing moment for a yawing velocity to the left, unstable damping in yaw was indicated. Calculations indicate this unstable damping in yaw to be a likely cause of the diverging lateral oscillation.

In order to study the damping in yaw more thoroughly, records were taken of coordinated turns of varying rates in near-autorotation and the results are presented in figure 5 in the form of pedal position plotted against rate of yaw. The points were obtained by reading for each turn the values of pedal position, yawing velocity, and sideslip angle during the turn at the instants when the yawing acceleration was zero and, hence, when the net yawing moment on the helicopter was zero. Other measurements showed no significant change in lateral stick position with rate of yaw and, hence, no yawing moments during the turns due to lateral stick motion. The results presented in figure 3 were used to subtract the pedal deflection needed to cancel the yawing moment due to sideslip; a process which, as mentioned previously, leaves the pedal deflection needed to cancel the yawing moment due to yawing velocity. The maximum correction for sideslip was 2 percent of pedal travel; the correction for most points was zero. Thus, the pedal position plotted in figure 5 is a direct measure of the yawing moment due to yawing velocity.

Figure 5 indicates the damping in yaw to be stable at low rates of yaw, but to become unstable at higher rates of yaw, thus confirming the previous indications. Whether this indication of unstable damping in yaw in autorotation and low power is a fuselage or fuselage-spoiler effect, or whether it is a basic tandem-rotor problem is not known.

Lateral Oscillations

In this section are presented studies of the lateral oscillatory characteristics of the test helicopter at the higher powers.

Original configuration.- In figure 6 are presented experimental and theoretical time histories of lateral oscillations of the test helicopter in level flight at approximately 70 knots, which is approximately its cruising speed.

Figure 6(a) is a measured oscillation for the original configuration. At this condition, as at all the higher-power conditions, the helicopter is statically stable directionally probably because of its vertical fins. However, as can be seen in the figure, it has a rapidly diverging oscillation which was, in this case, apparently initiated by a mild gust. The stick and pedals drifted somewhat during the oscillation but these drifts appear not to affect the oscillation significantly. The period of the oscillation is approximately 7 seconds and the amplitude doubles in approximately 1 cycle. As would be expected from the results of airplane stability studies, the oscillation was bothersome and was considered by the pilots to be an unsatisfactory characteristic.

The sideslip recorder is a multimirror instrument. Toward the end of the sideslip record presented in figure 6(a) large sideslip angles were reached; a condition which caused traces from other mirrors to appear on the film. The scales for these other mirrors are indicated at the traces. In order to clarify the curves, faired lines have been drawn also.

Analytical studies.- In order to provide a basis for improvement, analytical studies were made to see whether the oscillation could be predicted. Three degrees of freedom were considered: roll, yaw, and sideslip. The rotors were assumed to be at their equilibrium positions at all times, the positions being determined only by the instantaneous values of rolling velocity, yawing velocity, and sideslip angle. This assumption is sometimes referred to as a quasi-static approach. Thus, the analysis was rather similar to equivalent analyses for airplanes, such as those presented in references 2 and 3. However, whereas these references use a system of axes in which the X-axis is alined with the trim position of the relative wind, it was found more convenient to aline the X-axis with the principal longitudinal inertia axis which is approximately perpendicular to the rotor shafts. This choice was made in order to simplify the determination of stability derivatives from flight data inasmuch as the controls produce moments about axes approximately alined with the principal inertia axes. Therefore, the equations of motion were based on those of reference 4 which are set up to account for the selection of such a system of axis.

By using measured stability derivatives where possible, computing the remaining derivatives, and using inertia values supplied by the manufacturer, a theoretical oscillation due to a pulse lateral displacement of the control stick was predicted by an analogue computer for the test helicopter in its original configuration; the time history of this oscillation is presented in figure 6(b). As can be seen by comparison with the measured time history in figure 6(a), the period and rate of amplification of the oscillation were predicted rather well.

Further analytical studies show the main source of the instability to be a product-of-inertia effect due to the nose-down inclination with respect to the flight path of the principal longitudinal inertia axis. As indicated in the studies of reference 2, this inertia condition tends to produce oscillatory instability. The principal longitudinal inertia axis of the test helicopter is inclined between 5° and 10° nose down in level cruising flight. The product of inertia due to this inclination is accentuated by the fact that the moment of inertia in yaw is about 20 times greater than the moment of inertia in roll.

Inasmuch as changes in inertia characteristics were not considered practical methods of improvement, the analogue computer was used to make calculations in which only the stability derivatives were varied in order to find a basis for improvement. In figure 6(c) is presented a theoretically predicted time history of an oscillation for the test helicopter in the same condition as figures 6(a) and 6(b) except that the effective dihedral is reduced 50 percent. The result of the dihedral reduction is seen to be an oscillation of approximately constant amplitude, a significant improvement over the oscillation of figure 6(b).

Configuration as modified with small wings.- It was considered highly desirable to improve the oscillatory characteristics of the test helicopter to a satisfactory condition in order to provide a basis for establishing a flying-qualities criterion and also to determine whether the improvement predicted by theory could be verified experimentally. Studies indicated that the effective dihedral of the test helicopter could be conveniently reduced by means of small plywood wings attached to the main landing gear as shown in the sketch in figure 7. The sweepback of the wings combined with the down load on them during level forward flight produced by the nose-down inclination of the aircraft add to the negative effective-dihedral contribution of the wings. In addition, the low position of the wings on the fuselage produces a negative dihedral contribution because of wing-fuselage interference. (In ref. 3 the effects of various wing configurations on effective dihedral are summarized.)

Obtaining some of the negative dihedral from the down load on the wings is a desirable feature in that the dihedral reduction in autorotation (where the original value of dihedral is low and where there is an

up load on the wings) is smaller than the reduction in level flight. This effect plus an apparent change in the interference effect of the low wing position results in an autorotative dihedral reduction of about one-half of the level-flight reduction.

In figure 8 are presented plots of lateral stick and pedal position against sideslip angle for the test helicopter at approximately 70 knots in level flight for the original configuration and as modified with the small plywood wings. The slopes of the lateral-stick-position curves show that the effective dihedral is reduced to approximately one-half its original value by the presence of the plywood wings. The moderate increase in slope of the pedal-position curve for the configuration as modified with the small plywood wings is primarily caused by the reduction in lateral stick motion.

In figure 6(d) is presented an oscillation measured in flight for the configuration with the plywood wings added and at the same flight condition as for figure 6(a). Comparison of the measured oscillations presented in figures 6(a) and 6(d) with the theoretical oscillations presented in figures 6(b) and 6(c) shows good agreement in the improvement in oscillatory stability due to the one-half dihedral reduction.

Actually, the configuration as modified with the small plywood wings was also different from the basic configuration in that the spoilers used to obtain directional stability in autorotation were still attached. However, measurements of the lateral characteristics in level flight at 70 knots with only the spoilers on indicated little difference from the characteristics of the basic configuration. Thus, the improvement obtained with the modified configuration is concluded to be due primarily to the plywood wings.

The pilots were much impressed by the improvement in oscillatory characteristics produced by the plywood wings, but still did not consider the characteristics satisfactory.

Further modifications to test helicopter.- In an effort to obtain a satisfactory oscillatory condition, the plywood wings were replaced with wings of larger size, but insufficient improvement was obtained at the 70-knot level-flight condition. To enlarge the wings still further was not considered practical. By investigating various speed and power conditions, however, an oscillation that was considered by the pilots to be satisfactorily damped was obtained. A record of an oscillation at this satisfactory condition, which was at approximately 80 knots with power one-half that for level flight, is presented in figure 9. For this record, the oscillation was initiated with a pedal displacement rather than a lateral stick displacement.

An examination of the records in figure 9 shows the oscillation to damp to one-half amplitude in $1\frac{1}{2}$ to 2 cycles. (To determine the rate of damping more accurately is difficult because there seem to be small disturbances toward the end of the record, probably caused by mild air turbulence.) The additional improvement in characteristics at this condition is considered to be due, at least in part, to a removal of the adverse product-of-inertia effect in that the fuselage angle of attack was now approximately zero. In addition, a further reduction in effective dihedral was measured at this condition.

Although the pilots considered the improvement from the constant-amplitude-oscillation condition to the damped condition to be necessary for satisfactory flying qualities, they considered the initial improvement from the diverging-oscillation condition to the constant-amplitude-oscillation condition to be much more valuable.

Turn Characteristics

In this section are presented studies of the turn characteristics of the test helicopter at the higher powers.

Original configuration.- In figure 10 are presented experimental and theoretical time histories of attempted turns produced by lateral step displacements of the control stick with the pedals fixed for the test helicopter at approximately 70 knots in level flight. The step displacements of the lateral control are used in order to have representative repeatable maneuvers that can be directly compared with similar maneuvers at other conditions.

In figure 10(a) is presented an experimental time history for the original configuration. In order to clarify the sideslip curve, a faired line has been drawn. The rolling velocity can be seen to reverse after about 3 seconds. Even the yawing velocity is about to reverse when recovery control is applied. As would be expected from results of airplane stability studies, such as those reported in reference 1, the pilots considered this condition unsatisfactory.

Analytical studies.- The analytical studies of the lateral oscillation presented in figures 6(b) and 6(c) also included predictions of time histories produced by step displacements of the lateral control with the pedals fixed. The measured reversal in rolling velocity and the indicated reversal in yawing velocity of figure 10(a) were predicted rather well, as can be seen from the theoretical curves shown in figure 10(b).

In figure 10(c) is presented a theoretical time history produced by a step displacement of the lateral control with the pedals fixed for

the same flight condition as figures 10(a) and 10(b), but with one-half the effective dihedral. The elimination of the yawing-velocity reversal and the substantial reduction in the rolling-velocity reversal of figure 10(b) should be noted.

Configuration as modified with small wings.- In figure 10(d) are presented measured turn characteristics for the helicopter with the small plywood wings which reduced the effective dihedral. As can be seen by comparing this figure with figure 10(a), the reversal in yawing velocity is eliminated and the reversal in rolling velocity is almost eliminated; thus, the theoretically predicted improvement from figure 10(b) to figure 10(c) is approximately confirmed. Both test pilots considered the turn characteristics of the helicopter marginally satisfactory at this condition.

Adverse yawing moment due to lateral stick displacement.- As indicated in the calibrations presented in figure 2, a lateral stick displacement in the test helicopter produces an adverse yawing moment in addition to the usual rolling moment. This condition can be seen to be due to the larger amount of cyclic pitch on the rear rotor than on the front rotor produced by a given amount of lateral stick displacement. This rigging feature was taken into account in the theoretical curves of figure 10. As would be expected, the turn characteristics were made somewhat worse than if equal amounts of cyclic pitch were produced at both rotors.

Further modifications to test helicopter.- In figure 11 are presented turn-maneuver time histories for the configuration as modified with the larger plywood wings obtained at the higher-speed reduced-power flight condition at which satisfactory oscillatory characteristics were obtained. The pilots considered the characteristics of the turn presented in figure 11(a), which was made with the pedals fixed, to be satisfactory inasmuch as there was no reversal in rolling or yawing velocity. Flying in rough air was reported to be relatively easy at this condition of speed and power. However, the pilots indicated that, if feasible, they would prefer to have less sideslip build up during the pedal-fixed turn maneuver. Such a reduction in sideslip could be obtained if the lateral stick motion were made to produce a favorable yawing moment; a control condition which could be obtained relatively easily in a tandem helicopter by having a lateral stick motion produce more lateral cyclic pitch on the front rotor than on the rear rotor (the reverse of the rigging existing in the test helicopter).

In order to check this line of reasoning, the maneuver shown in figure 11(b) was performed. In this maneuver, the pedals were displaced simultaneously with the stick so that the lateral tilt of the front rotor was greater than that of the rear rotor. These control motions simulated a lateral step displacement of the stick with the pedals fixed, with

modified rigging. The turn characteristics for this method of control were much improved, as indicated by the fact that the rolling velocity shows very little tendency to fall to zero and the maximum sideslip angle is about the same as in the turn maneuver of figure 11(a) even though the lateral control deflection of figure 11(b) is about twice as big as that of figure 11(a). The pilots, who judged the maneuver as though it were pedal-fixed, thought they would like this modified type of lateral stick control in forward flight. There remains, however, the necessity of determining possible adverse characteristics of such a control in hovering, where the pilot might object to the yawing acceleration produced by lateral stick motion. To do this would require rerigging the helicopter so that the pilots would have an independent pedal control along with the modified lateral stick control. Such a project was considered beyond the scope of the present program.

CRITERIA FOR SATISFACTORY HELICOPTER LATERAL FLYING QUALITIES

On the basis of the results presented herein, the results of single-rotor helicopter stability studies reported in reference 5, some unpublished single-rotor helicopter stability studies, and airplane flying-qualities studies such as those reported in reference 1, the following sections are believed to summarize some important goals for satisfactory lateral flying qualities of all types of helicopters. Further work covering flight conditions different from those studied may indicate additional goals to be desirable.

The goals in the following sections are considered to be applicable throughout the available power range and at all speeds considered to be within the forward-flight regime. The speed for maximum rate of climb is the minimum forward speed at which prolonged flight occurs. Thus, the forward-flight regime is considered to include all forward speeds above 0.8 times the speed for maximum rate of climb; the 0.8 factor allows some margin for inadvertent deviations from the desired speed.

Directional Stability

At all speeds above 0.8 times the speed for maximum rate of climb, the helicopter should possess pedal-fixed static-directional stability such that right rudder-pedal deflection from the position for straight flight is required for steady left sideslips and vice-versa. For angles of sideslip between

$\pm 15^{\circ}$, the change in angle of steady sideslip should be substantially proportional to the pedal deflection from its straight-flight setting. For sideslip angles greater than 15°, increase in pedal deflection should be required to produce increases in steady sideslip angle up to full pedal deflection.

Lateral Oscillations

At all speeds above 0.8 times the speed for maximum rate of climb, with controls fixed, all lateral oscillations with periods less than 10 seconds should damp to one-half amplitude in less than 2 cycles (at least 30-percent amplitude reduction per cycle) and there should be no noticeable residual oscillation.

The period of the lateral oscillation of the helicopter tends to be larger than that normally obtained in airplanes. Reference 5 indicates that long-period longitudinal oscillations of the helicopter may be moderately divergent and still be satisfactory. Further study may indicate a similar condition for lateral oscillations.

Turn Characteristics

At all speeds above 0.8 times the speed for maximum rate of climb, no reversal of rolling velocity should occur within 6 seconds after a small lateral step displacement of the control stick with pedals fixed. The stick deflection chosen should be such that the maximum angle of bank reached during the 6-second period is approximately 30°.

Inasmuch as the response of the helicopter may be of different nature for stick deflections of different magnitudes, a stick deflection which results in the specified maximum angle of bank is called for in order to make certain that the turning characteristics are determined under conditions corresponding to a maneuver of practical magnitude.

MEANS OF ACHIEVING DESIRED LATERAL FLYING QUALITIES IN THE TANDEM HELICOPTER

Directional Stability

Calculations indicate that modification of the rotors is not a very effective method of achieving directional stability. For example, if the stability with forward speed of the front rotor, and hence, as explained subsequently, the side force due to sideslip, were reduced to zero by such means as tabs on the blades to produce cyclic blade twisting, an increment in directional stability of only approximately 30 percent of the instability of the original helicopter in autorotation would be obtained. Thus, improvments in directional stability must be obtained by modification of the fuselage-empennage characteristics.

Previously mentioned was the fact that wind-tunnel tests of a model of the fuselage-empennage combination of the test helicopter indicate directional instability at positive angles of attack, as in autorotation. These tests also indicate the fuselage-empennage combination to be stable directionally at negative angles of attack, as in power-on flight. These characteristics compare favorably with the measured directional stability of the test tandem helicopter in autorotation and power-on flight, respectively. Thus, wind-tunnel tests of tandem-helicopter fuselage-empennage combinations seem to give qualitatively correct directional-stability results despite the absence of rotors and rotor downwash and hence are indicated to be one effective way of studying methods of improving pedal-fixed directional stability.

Oscillatory and Turn Characteristics

The experimental verification of the theoretically predicted improvement in oscillatory and turn characteristics due to the reduction in effective dihedral shown in figures 6 and 10 indicates that the stability analysis described in the section entitled "Lateral Oscillations" is a useful tool for studying methods of improving helicopter lateral stability. Thus, the following changes in stability derivatives were studied analytically:

Reduction in effective dihedral

Increase in damping in roll

Positive rolling moment due to yawing

Increase in directional stability

Increase in damping in yaw

Positive and negative yawing moment due to rolling

Inasmuch as the results were similar for the oscillations and turn maneuvers, only the oscillation results are discussed. The detailed analyses used to obtain these results are considered to be beyond the scope of the present paper and hence are not presented herein. As is indicated subsequently, however, the results discussed are generally applicable to various types of tandem helicopters.

Effects of variations in stability derivatives.- The improvement in oscillatory characteristics due to reduced effective dihedral has already been mentioned. A damping of the oscillation was also produced by an increase in damping in roll and, to a lesser extent, by positive rolling moment due to yawing; that is, a rolling moment to the right produced by a yawing velocity to the right.

On the other hand, an increase in directional stability was found to be relatively ineffective in that a tenfold increase was indicated to be necessary to damp the oscillation adequately. Thus, although the autorotation investigation indicates directional instability to be unsatisfactory, attempting to achieve satisfactory oscillatory characteristics by means of increases in directional stability does not appear to be practical. Large increases in damping in yaw produced practically no improvement in the oscillatory characteristics. Thus, the approach of using a yaw damper to improve lateral oscillatory characteristics, which has been used on some airplanes, does not appear to be applicable to the tandem helicopter. Both positive and negative yawing moment due to rolling made the oscillations worse.

Those derivatives producing rolling moments appear to be much more effective than those derivatives producing yawing moments. The reason for this condition is thought to be, at least in part, the low moment of inertia in roll as compared with the moment of inertia in yaw; the rolling moments are thus much more effective.

Factors affecting stability derivatives.- In order to be able to make the changes in stability parameters suggested by theory, it is necessary to understand the factors that affect the various stability parameters. In figure 12 is presented an explanation of the source of the three important stability parameters: effective dihedral, damping in roll, and rolling moment due to yawing.

Inasmuch as a conventional helicopter has no fixed wing to produce dihedral, the effective dihedral is produced by the fuselage-empennage combination and by the rotors. The rotor contribution is produced as follows: The helicopter rotor is stable with speed changes, as discussed

in reference 6, in that an increase in forward speed produces a nose-up moment by causing a rearward tilt of the tip-path plane. This rearward tilt is produced in order to equalize the dissymmetry in lift between advancing and retreating blades. Similarly, a sideslip velocity to the left, for example, as shown in figure 12, will produce a tilt of the tip-path plane to the right to equalize lift dissymmetries. This tilt produces a tilt of the thrust vector to the right and hence a rolling moment to the right.

Damping in roll is produced by a lagging of the tip-path plane and (normally) the rotor-thrust vector behind the fuselage due to a rolling velocity as discussed in references 6 and 7. Thus, as shown in figure 12, a rolling moment to the right is normally produced by a rolling velocity to the left.

A rolling moment due to a yawing velocity is produced as follows: A yawing velocity to the left, for example, produces a sideslip velocity to the left at the front rotor and a sideslip velocity to the right at the rear rotor. Because of the effective dihedral of the rotors, these opposite sideslip velocities produce opposite rotor tilts, as shown in figure 12. A yawing moment that opposes the yawing velocity is produced, but, much more important, if the rolling moment of one rotor is larger than that of the other rotor, a net rolling moment will result. For example, as shown in figure 12, if the rolling moment of the rear rotor is greater, a net rolling moment to the left will result from the yawing velocity to the left. Normally, however, the rolling moments of the two rotors are approximately equal.

Methods of varying stability derivatives.- With this understanding of the source of the three important stability derivatives, some possible practical methods of varying these derivatives in order to improve tandem-helicopter lateral stability can be discussed. Calculations indicate that, for the test helicopter, a 65-percent reduction in effective dihedral is one method of obtaining damping to half-amplitude in 2 cycles. As discussed in the section on criteria, this rate of damping appears to be somewhere near the minimum satisfactory for helicopters. It should be pointed out that, because of the axis system used in the analysis, the effective dihedral is defined as the rolling moment about the principal longitudinal inertia axis due to sideslip.

One way to achieve at least part of this 65-percent reduction in effective dihedral might be by modifications of the fuselage or of the tail surfaces or, as on the test helicopter, by means of landing-gear fairings. It appears likely that such modifications could be conveniently studied in a wind tunnel. The vertical center-of-gravity position, however, must be known accurately. Flight measurements indicate the center of gravity to be only a short distance below the lateral center of pressure. Thus, small vertical center-of-gravity changes are

indicated to have a large effect on the contributions of the fuselage and the vertical stabilizers to effective dihedral.

There are also ways of achieving additional dihedral reduction by reduction in the stability with forward speed of the individual rotors. One way to accomplish this dihedral reduction on the rotors might be by using tabs on the blades to produce cyclic blade twisting. Reference 8 indicates that the stability with speed of an individual rotor is approximately uniform throughout the speed range. Equation (43) of reference 9 indicates that, if the blade chordwise center of gravity and the aerodynamic center are coincident, then a section moment coefficient causes a cyclic blade twisting proportional to the first power of the tip-speed ratio. Thus, under such conditions blade tabs would cause a uniform reduction in stability with speed of the individual rotor throughout the speed range.

To achieve the entire 65-percent dihedral reduction with rotor modifications would require a 130-percent reduction in rotor stability with speed. This change would mean making the individual rotor stability with speed negative. Inasmuch as pitching moments on the tandem helicopter are produced mainly by differences in thrust, the contribution of the individual rotors to stability with forward speed is small and hence can be relatively easily substituted for. However, it is not likely that enough blade twisting could be tolerated to permit making all the dihedral reduction by that means. Also, as indicated subsequently, a preferable procedure might be to work with the front rotor only and accept one-half as much dihedral reduction.

Calculations indicate that approximately a 170-percent increase in damping in roll is required to produce damping of the oscillation to half-amplitude in 2 cycles. One way to achieve such an increase would be by increasing the blade moment of inertia about the flapping hinge by 170 percent. A jet-driven helicopter inherently incorporates an increase in blade moment of inertia of this magnitude. Alternatively, a gyroscopic device might be used to achieve an equivalent increase in tip-path-plane tilt due to rolling velocity. Increases of this magnitude were obtained during flight tests of a helicopter with such a device reported in reference 5.

Calculations indicate that offsetting the flapping hinges of the rear rotor radially 20 percent of the radius would also produce damping of the oscillation to half-amplitude in 2 cycles. Such a design modification increases the rolling moment due to a tilt of the rear rotor and hence a yawing velocity to the right will produce a rolling moment to the right. The improvement due to this modification is also partly due to an increase in the damping in roll. Offsetting the flapping hinges increases both damping in roll and effective dihedral by increasing the rolling moment due to a given rotor tilt. The increase in damping in

roll is good; the increase in dihedral is bad. For the test helicopter, this amount of offset of the flapping hinge produces a substantially larger percentage increase in damping in roll than in effective dihedral.

Another method of achieving a rolling moment to the right due to a yawing velocity to the right might be to reduce the stability with speed and hence the effective dihedral of the front rotor only. As indicated previously, reduction in effective dihedral is desirable and might be accomplished by tabs on the rotor blades to produce cyclic blade twisting.

Figure 13 indicates the way offsetting the flapping hinge radially increases the rolling moment due to rotor tilt. Normally, the rolling moment is produced entirely by a tilt of the thrust vector. When the flapping hinges are offset, the mass forces on the blades add to the rolling moment.

One factor must be considered in the use of offset hinges on the rear rotor. The control rigging may have to be arranged so that a pedal motion produces more lateral cyclic pitch on the front rotor than on the rear rotor in order that no rolling moment will result from pedal displacement.

Actually, there are more than half a dozen design changes which are, at least to some extent, under the designer's control which could be used to change one or more of the three significant derivatives. It appears that the required magnitude of any one design change will usually be found to be too big to be practical; however, by combining smaller amounts of several design changes, satisfactory lateral stability probably could be achieved.

Effect of rotor overlap.- There are currently in production two somewhat different types of tandem-rotor helicopters - the type, such as the test helicopter, in which there is no overlap of the rotor disks and the type in which the disks do overlap, usually with the rear rotor somewhat higher than the front rotor. Inasmuch as there is some question as to whether the conclusions presented in the section "Methods of varying stability derivatives" as to methods of improving oscillatory and turn characteristics would apply to the overlap type of tandem helicopter, the analysis was repeated for a helicopter with an amount of overlap typical of current practice.

For the original overlap configuration used in the analysis, the test helicoper in its original configuration was assumed to be shortened longitudinally, the gross weight and the vertical and lateral dimensions remaining unchanged. Thus, the inertia in roll, damping in roll, and effective dihedral remain unchanged. The inertia in yaw and damping in yaw were assumed to decrease as the square of the length, and the directional stability was assumed to decrease as the first power of the length.

Thus, the directional stability was somewhat higher, in relation to the inertia in yaw and damping in yaw, than for the test helicopter. The one other change made was to assume the rear rotor higher than the front rotor (the average height remaining unchanged). Thus, yawing to the right produced some rolling moment to the right.

By using these characteristics for the basic configuration of the overlap type of helicopter, the same three stability parameters as before were found to be effective in producing damping of the oscillation. However, somewhat smaller parameter changes were needed than for the non-overlap type of helicopter, probably because the basic overlap configuration used has an oscillation that is somewhat less unstable. The three parameters which were previously found to be ineffective were once again found to be so.

CONCLUSIONS

The indications of studies of the lateral-directional flying qualities of a tandem-rotor helicopter in forward flight may be summarized as follows:

1. In relation to the pilot's satisfaction with the lateral-directional flying qualities of any type of helicopter, some important considerations are: the presence of static directional stability, reasonably well damped lateral-directional oscillations, and no reversal in rolling velocity in a turn produced by a step lateral displacement of the control stick, the pedals remaining fixed.

2. Wind-tunnel tests of the directional stability of a helicopter model without rotors show qualitative agreement with flight results, despite the absence of the rotors, and hence are indicated to be one effective method of studying means of improving tandem-helicopter static directional stability.

3. The improvement in oscillatory and turn characteristics of a tandem helicopter caused by changes in stability derivatives can be theoretically predicted if the changes in the stability derivatives can be accurately predicted or are measured in flight. Thus, stability theory is indicated to be a useful tool for studying methods of improving tandem-helicopter lateral stability.

4. The oscillatory and turn characteristics of a tandem helicopter can be significantly improved by a reduction in effective dihedral, by an increase in damping in roll and, to a lesser extent, by positive rolling moment due to yawing (a rolling moment to the right produced by a yawing velocity to the right). An understanding of the source of these

stability parameters suggests possible practical methods of achieving satisfactory lateral characteristics. In the practical case, it is probably necessary to use a combination of these design changes in order to avoid making large changes in any one design parameter with possible adverse complications.

5. The turn characteristics of the tandem helicopter can be improved still further by rigging the controls so that a lateral stick motion produces a favorable yawing moment in addition to the usual rolling moment. There remains, however, the necessity of determining possible adverse characteristics of such a control in hovering.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 7, 1953.

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TABLE I.- PRINCIPAL DIMENSIONS AND APPROXIMATE PHYSICAL CHARACTERISTICS OF TEST HELICOPTER

Gross weight, lb	7,000
Pitching moment of inertia, slug-ft^2	40,000
*Rolling moment of inertia about longitudinal axis perpendicular to rotor shafts, slug-ft^2	1,900
*Yawing moment of inertia about axis parallel to rotor shafts, slug-ft^2	40,000
Height of rotor hub with respect to center of gravity, ft	6
Number of rotors	2
Number of blades per rotor	3
Diameter of each rotor, ft	41
Distance between rotor shafts, ft	42.3
Solidity (chord weighted proportional to radius^2)	0.052
Ratio of thrust coefficient to solidity	0.08
Blade mass factor (ratio of air forces to inertia forces)	9
Horizontal stabilizer area, ft^2	40
Total vertical stabilizer area, ft^2	50
Aspect ratio of vertical stabilizers	1.4

*These axes are estimated to be very close to the principal inertia axes.

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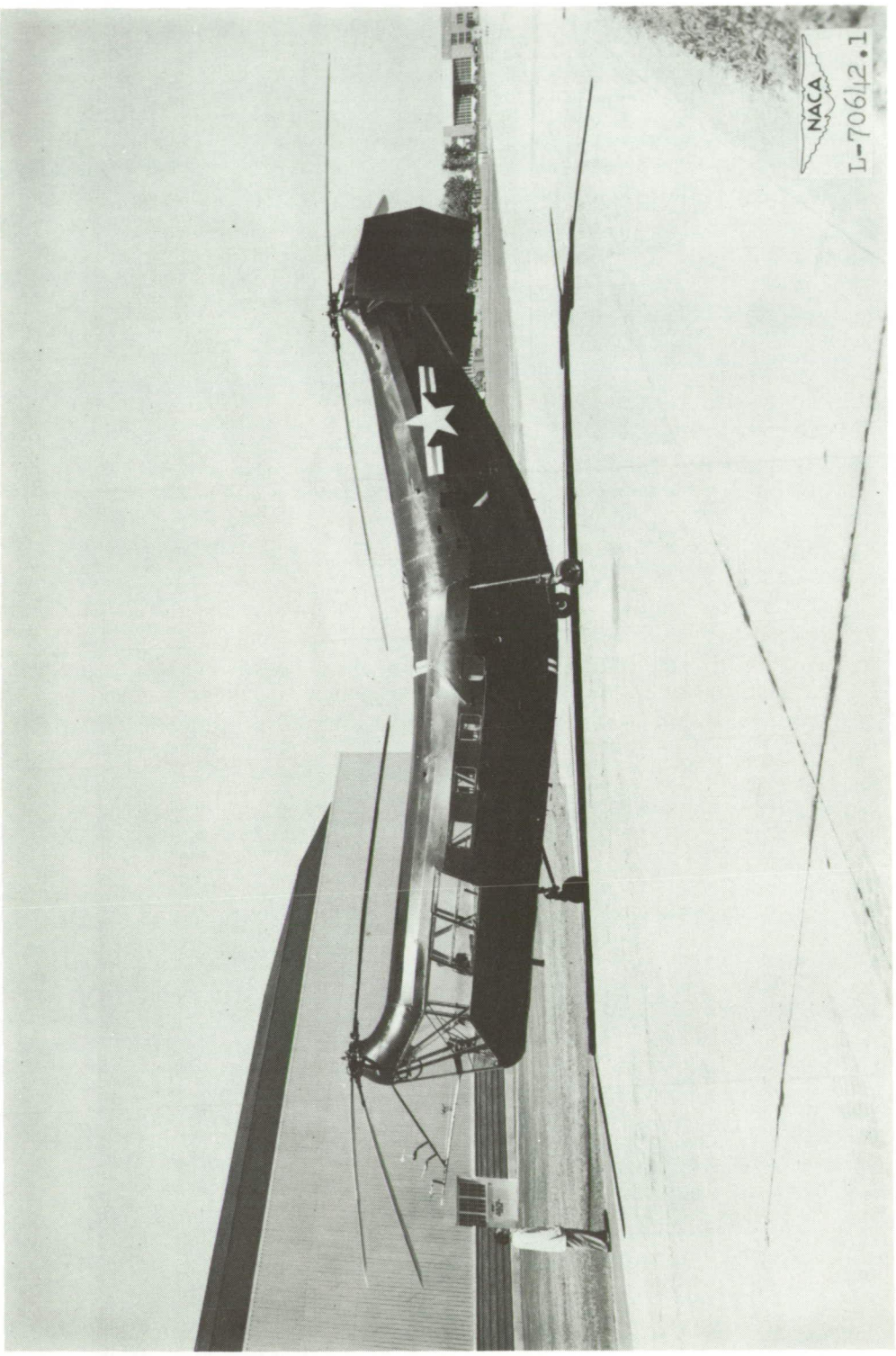
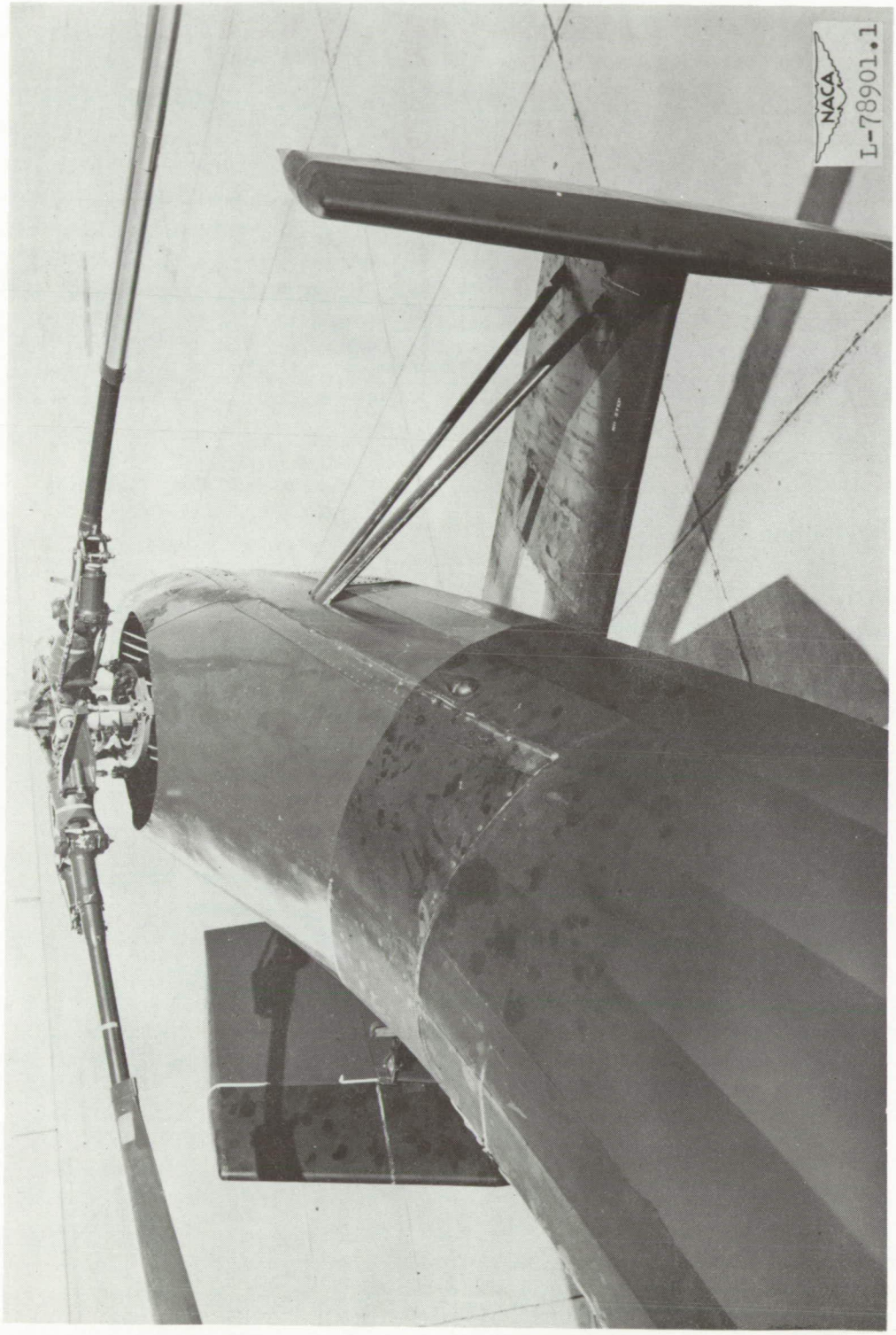


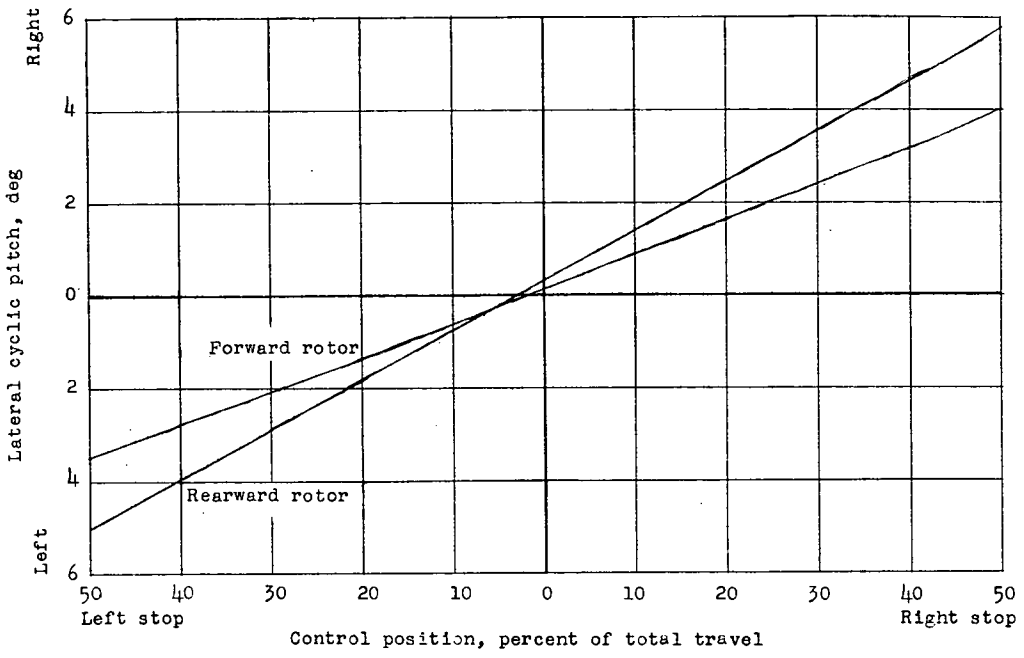
(a) Side view.

Figure 1.- Test helicopter.

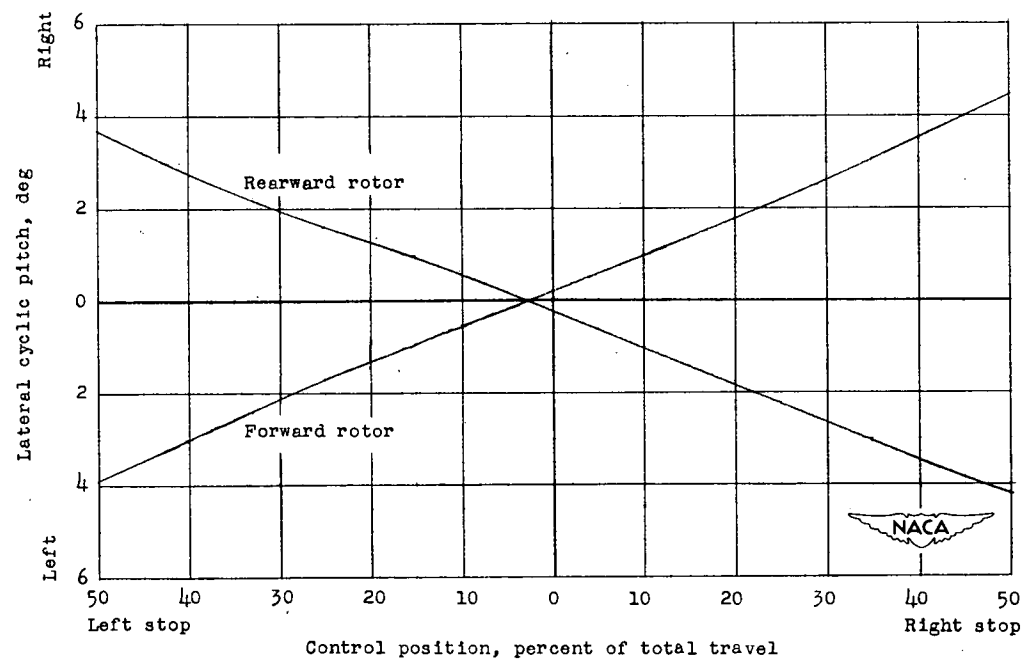


(b) Empennage.

Figure 1.- Concluded.



(a) Lateral stick deflection.



(b) Pedal deflection.

Figure 2.- Lateral cyclic pitch due to lateral stick and pedal deflection on test helicopter. Maximum stick travel, 8 inches; maximum pedal travel, 8 inches.

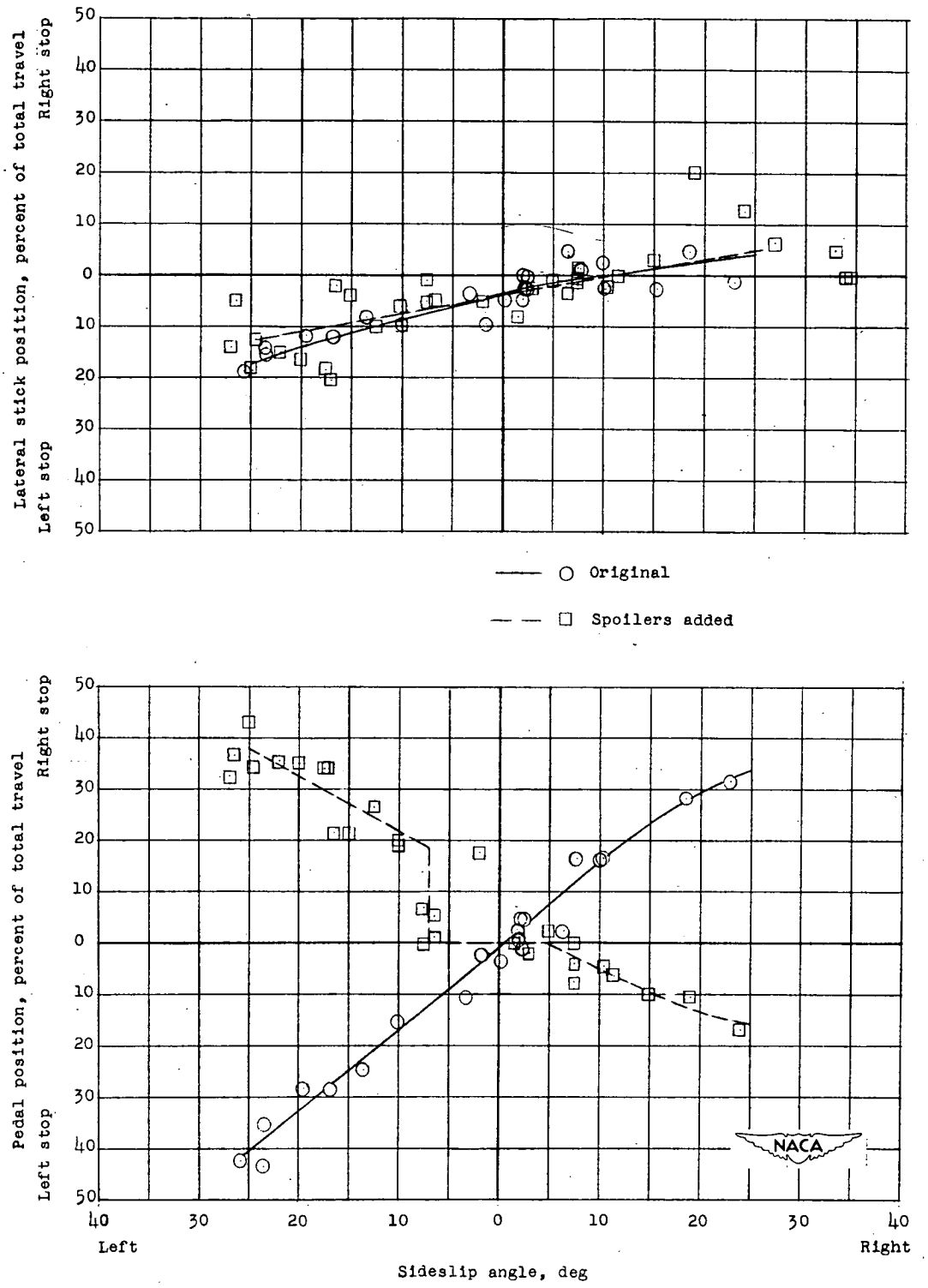


Figure 3.- Lateral stick and pedal position plotted against sideslip angle for test helicopter in autorotation at approximately 70 knots in original configuration and as modified with spoilers.

Figure 4.- Spoiler installation on test helicopter.

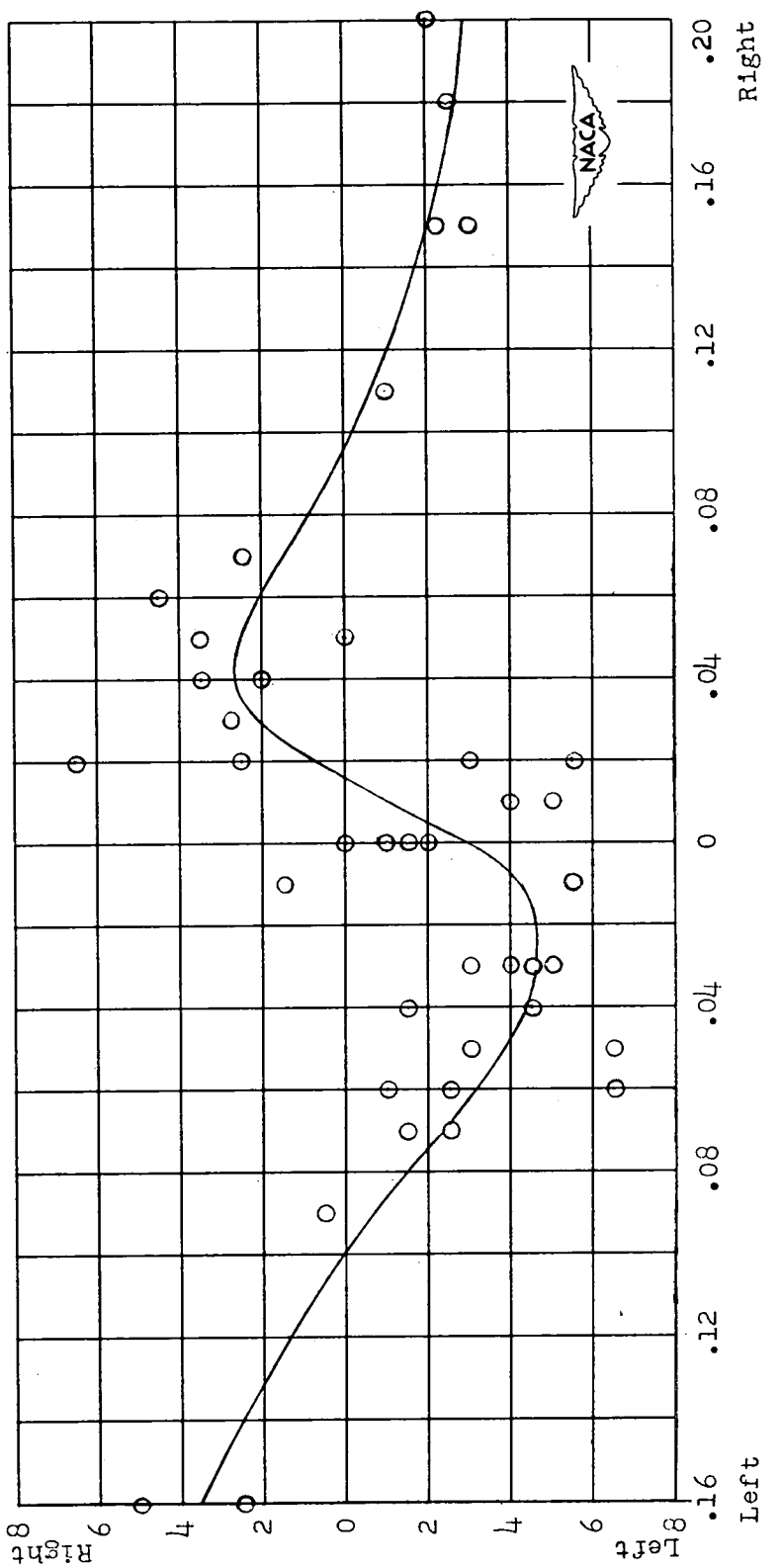
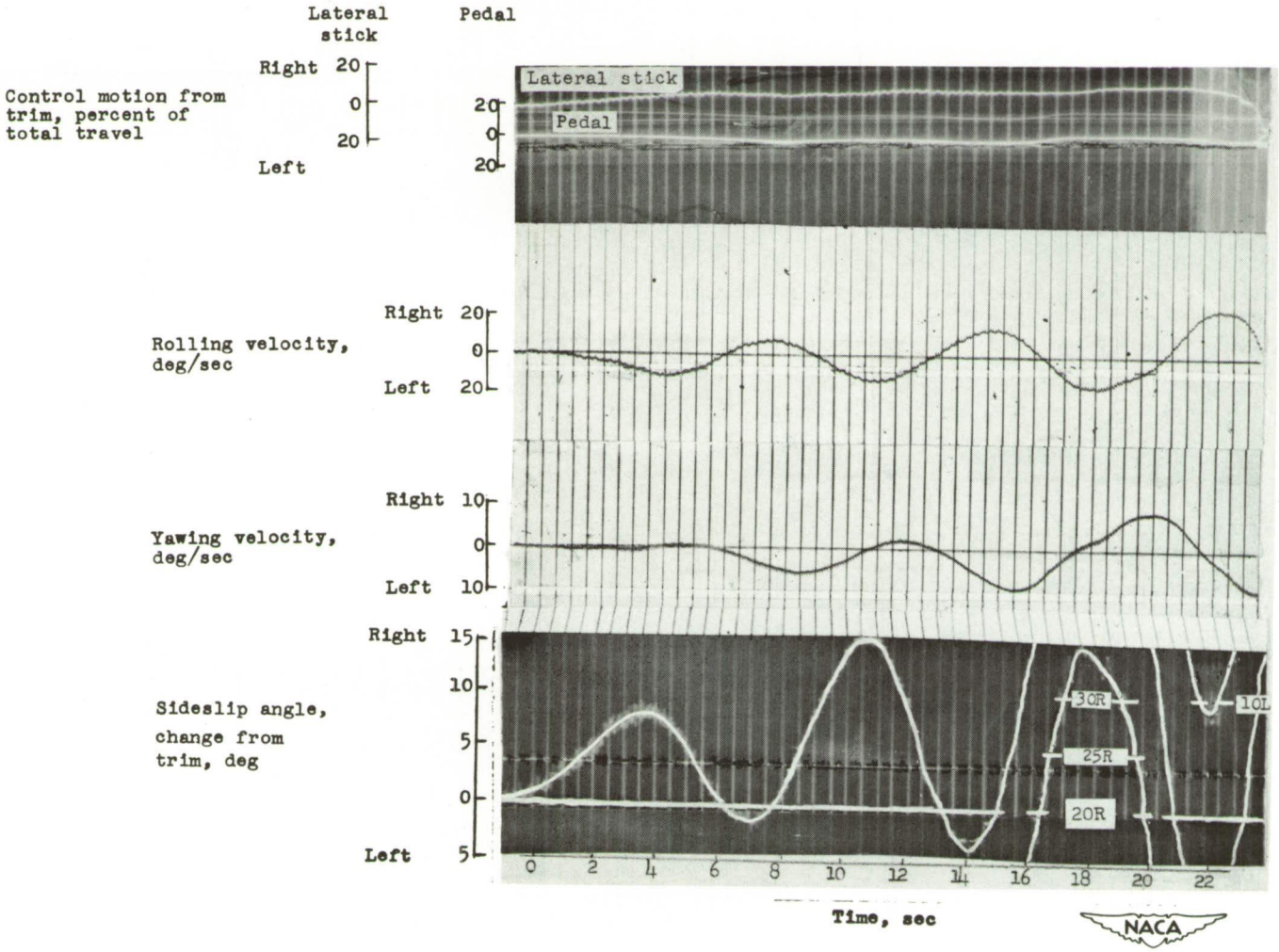
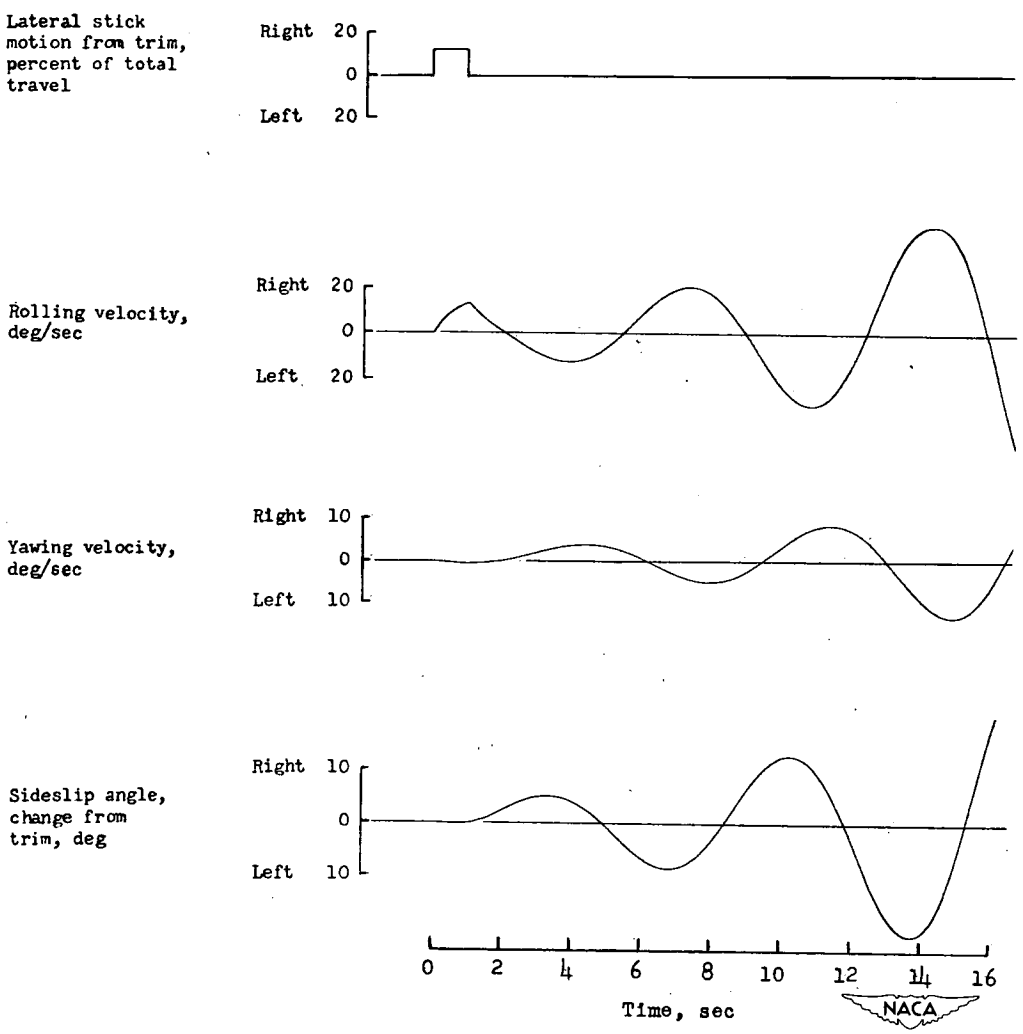


Figure 5.- Pedal position plotted against rate of yaw during coordinated turns at 70 knots in near-autorotation; spoilers attached.



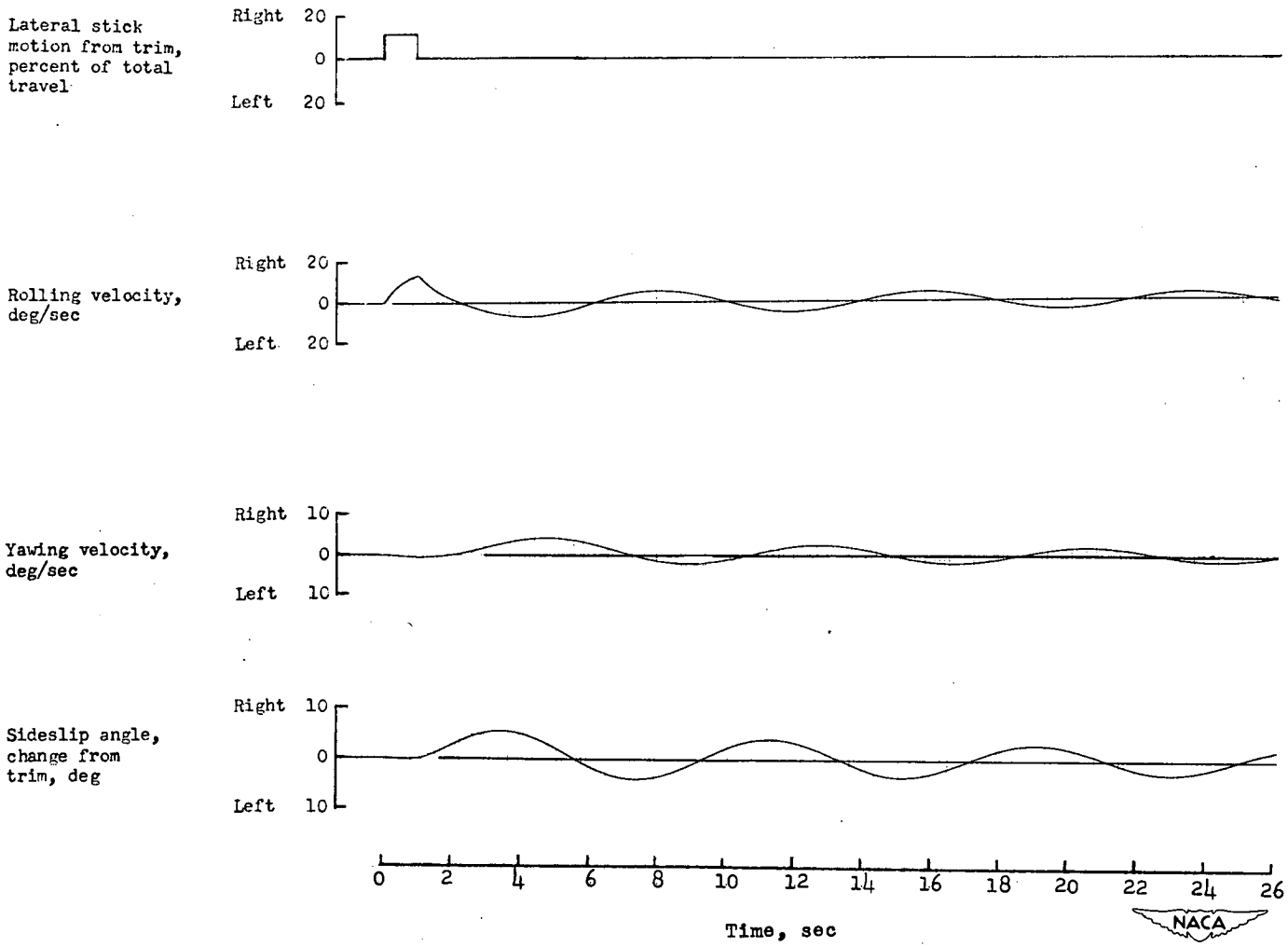
(a) Original configuration, experimental.

Figure 6.- Experimental and theoretical oscillations with controls fixed for test helicopter at approximately 70 knots in level flight.



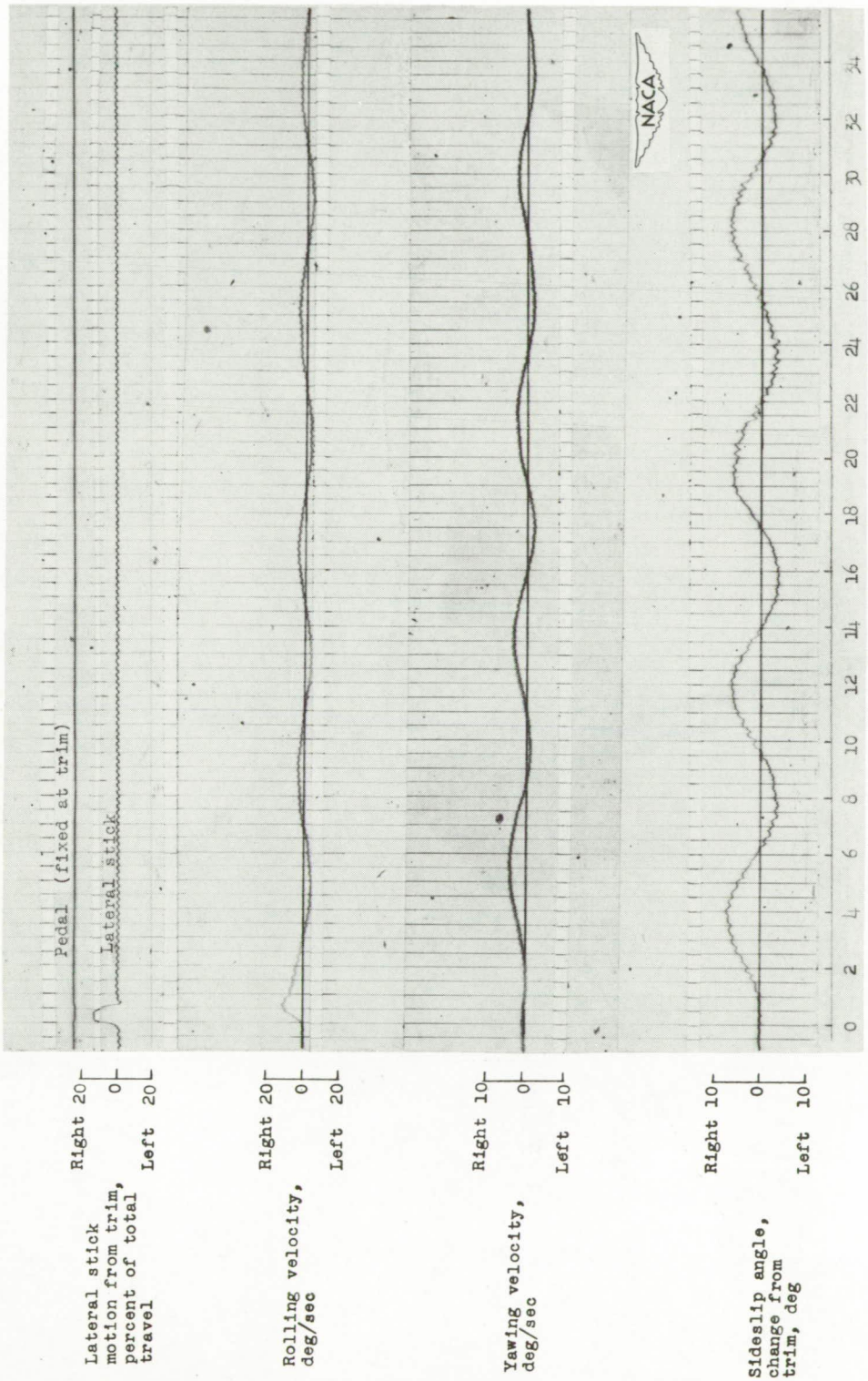
(b) Original configuration, theoretical.

Figure 6.- Continued.



(c) Effective dihedral reduced 50 percent, theoretical.

Figure 6.- Continued.



(d) Effective dihedral reduced 50 percent, experimental.

Figure 6.- Concluded.

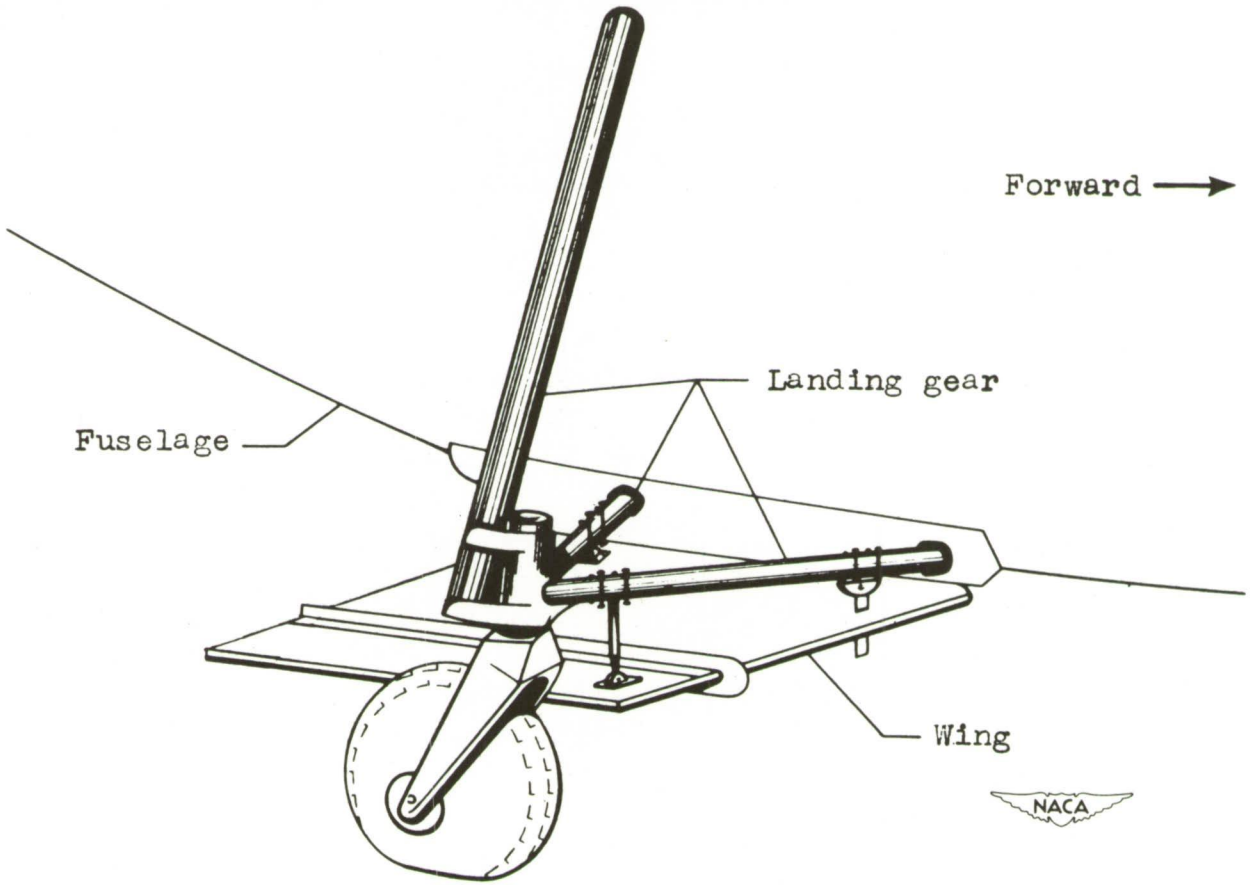


Figure 7.- Sketch of one of the small plywood wings attached to main landing gear of test helicopter to reduce effective dihedral. Area, 7 sq ft; aspect ratio, 1; sweepback, 45°; dihedral, -30°.

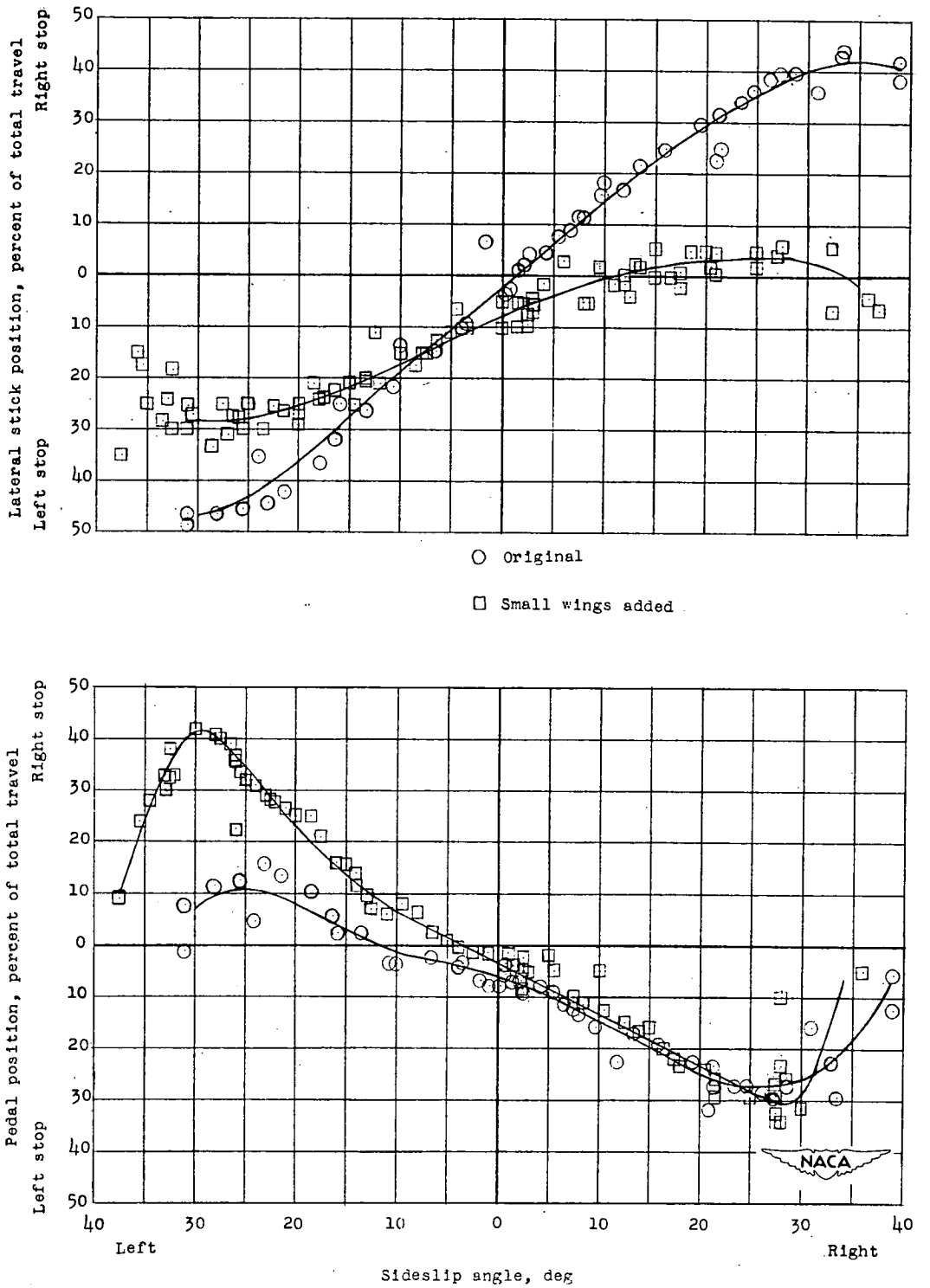


Figure 8.- Lateral stick and pedal position plotted against sideslip angle for test helicopter at approximately 70 knots in level flight in original configuration and as modified with small plywood wings.

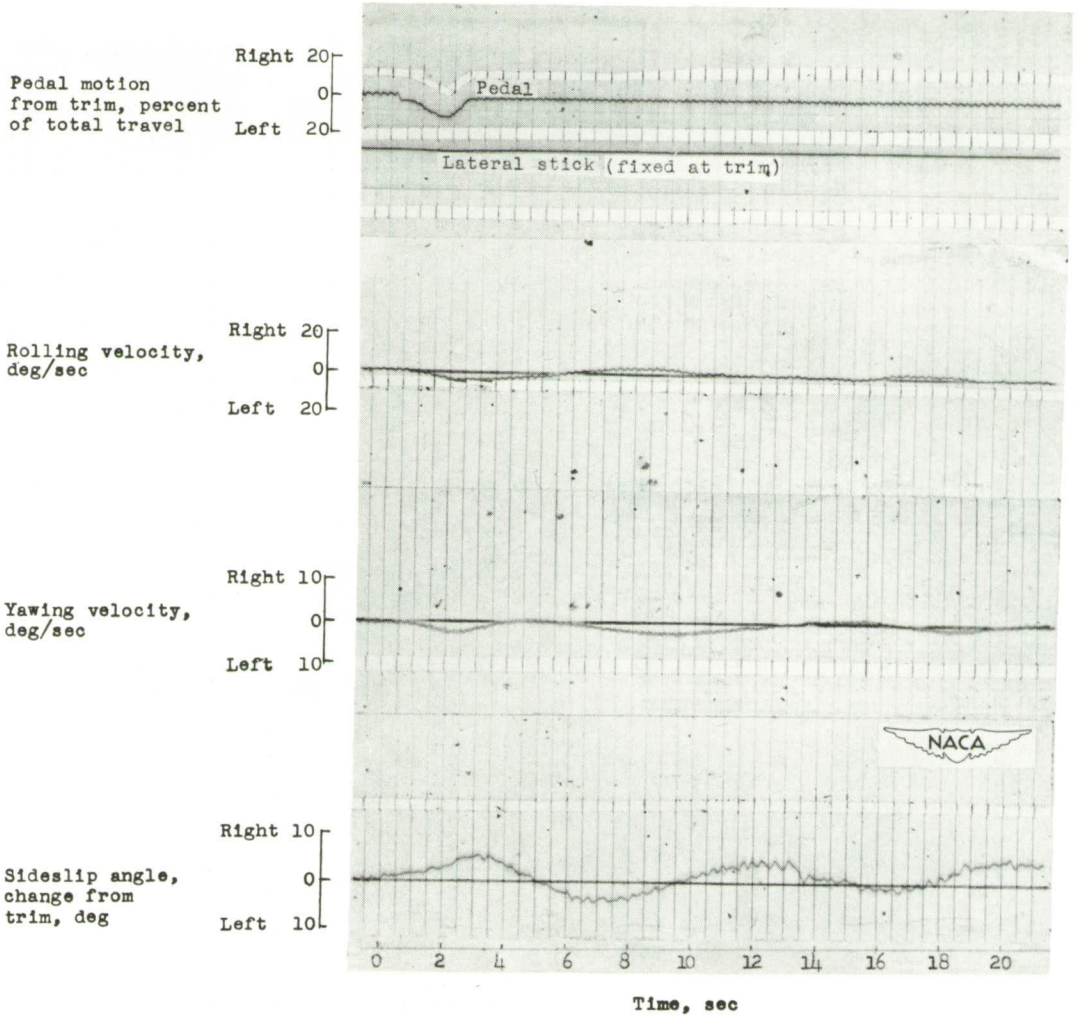
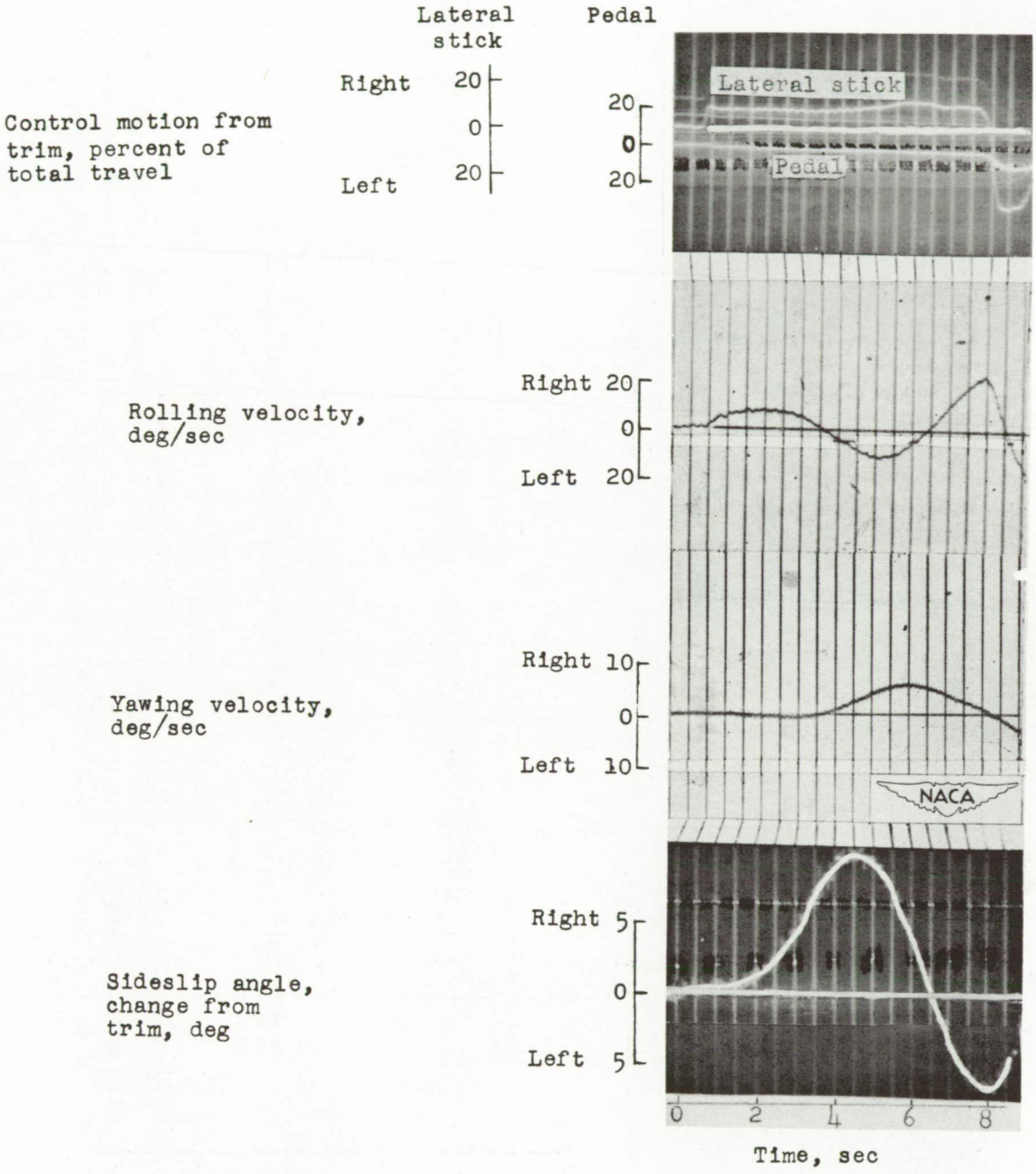
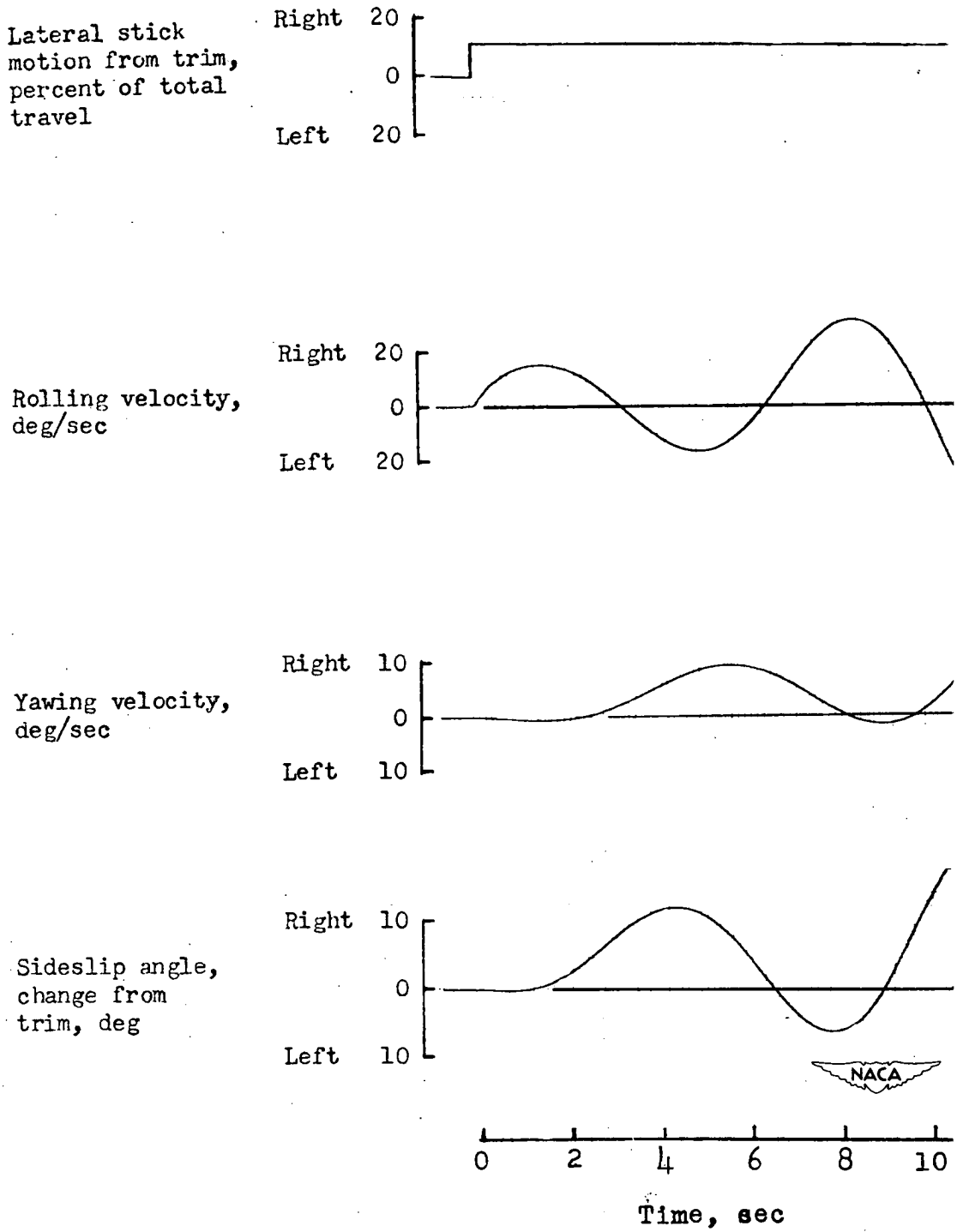


Figure 9.- Controls-fixed oscillation for test helicopter at approximately 80 knots; power one-half that for level flight; large plywood wings attached.



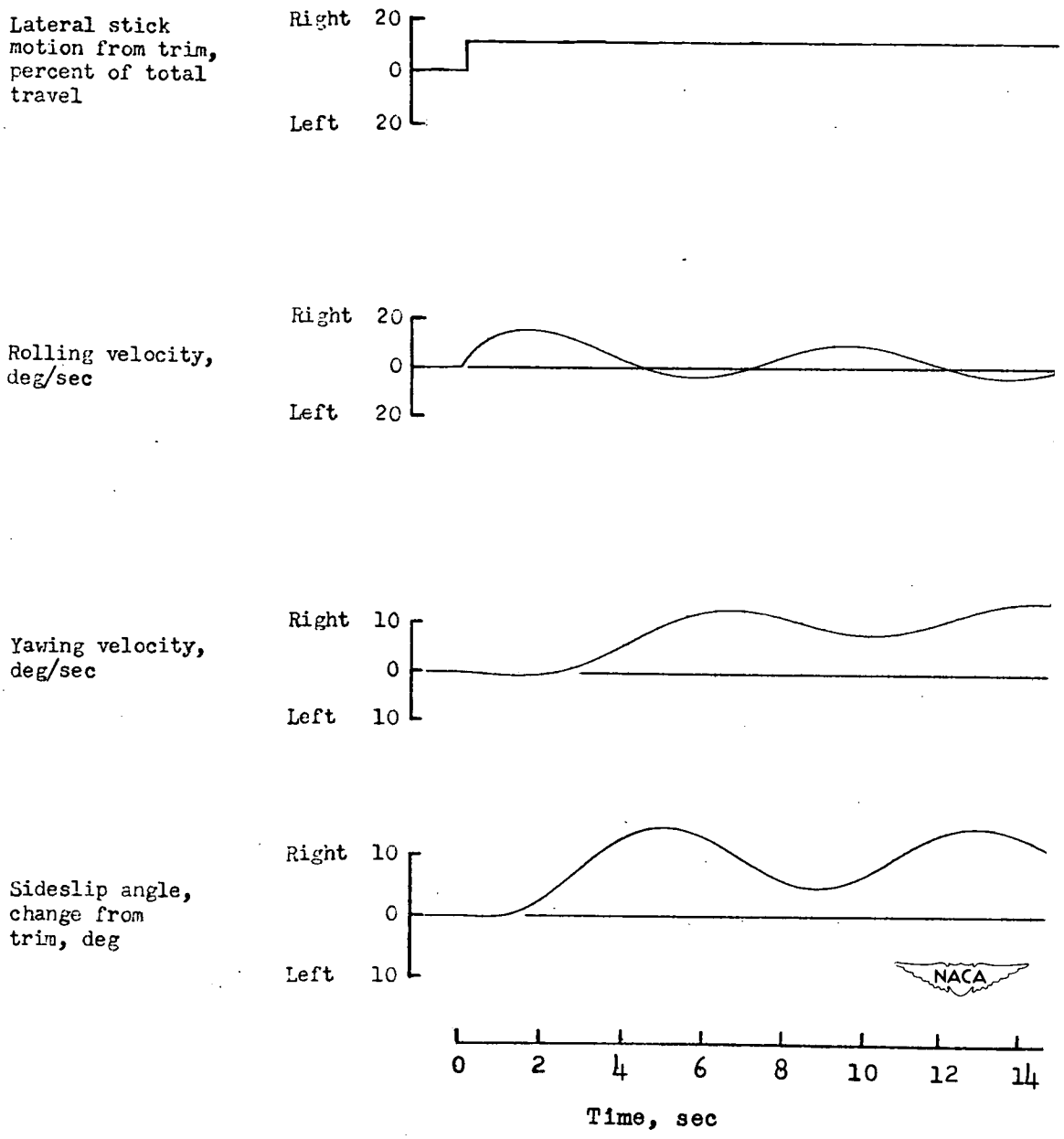
(a) Original configuration, experimental.

Figure 10.- Experimental and theoretical time histories of attemped pedal-fixed turns for test helicopter at approximately 70 knots in level flight.



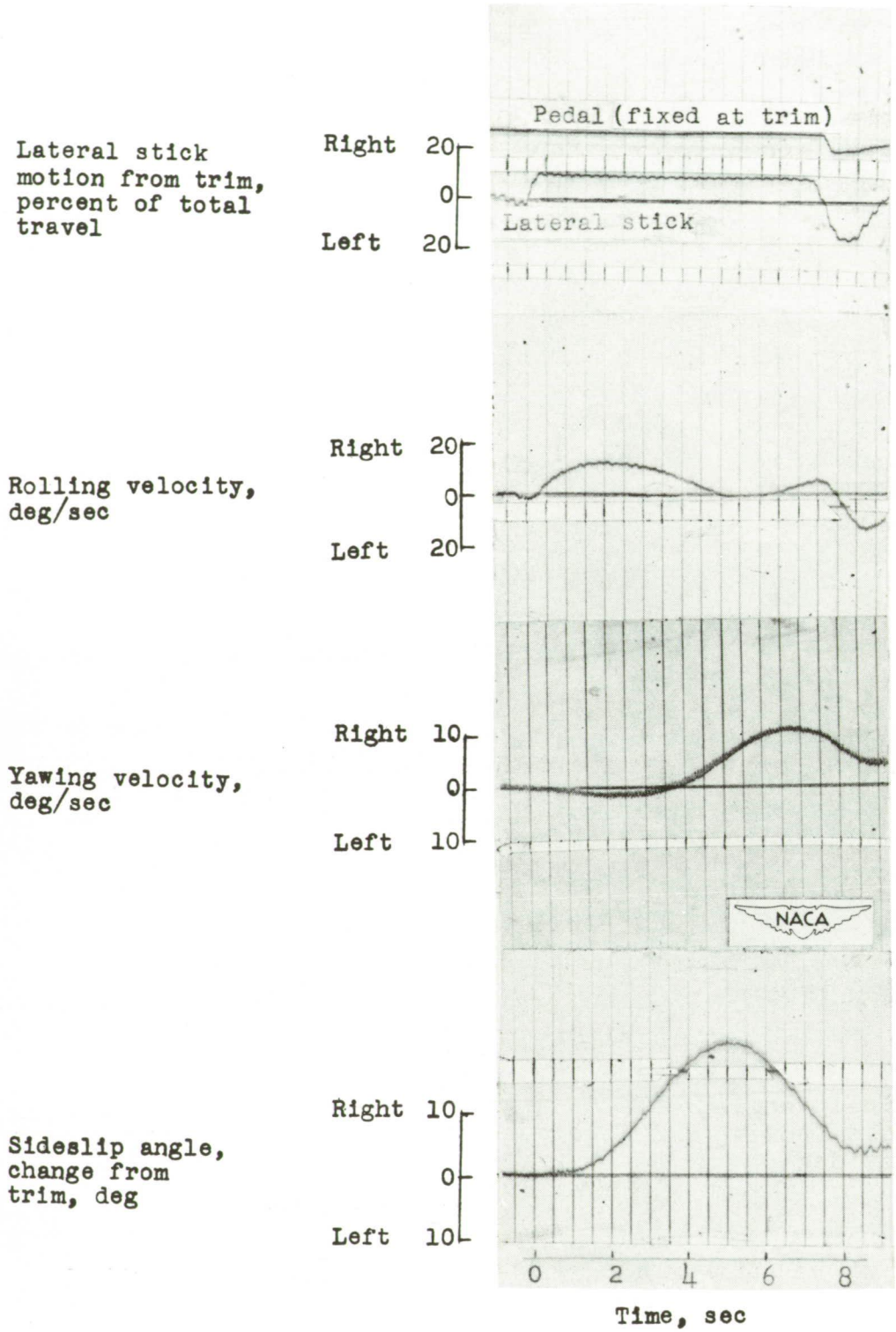
(b) Original configuration, theoretical.

Figure 10.- Continued.



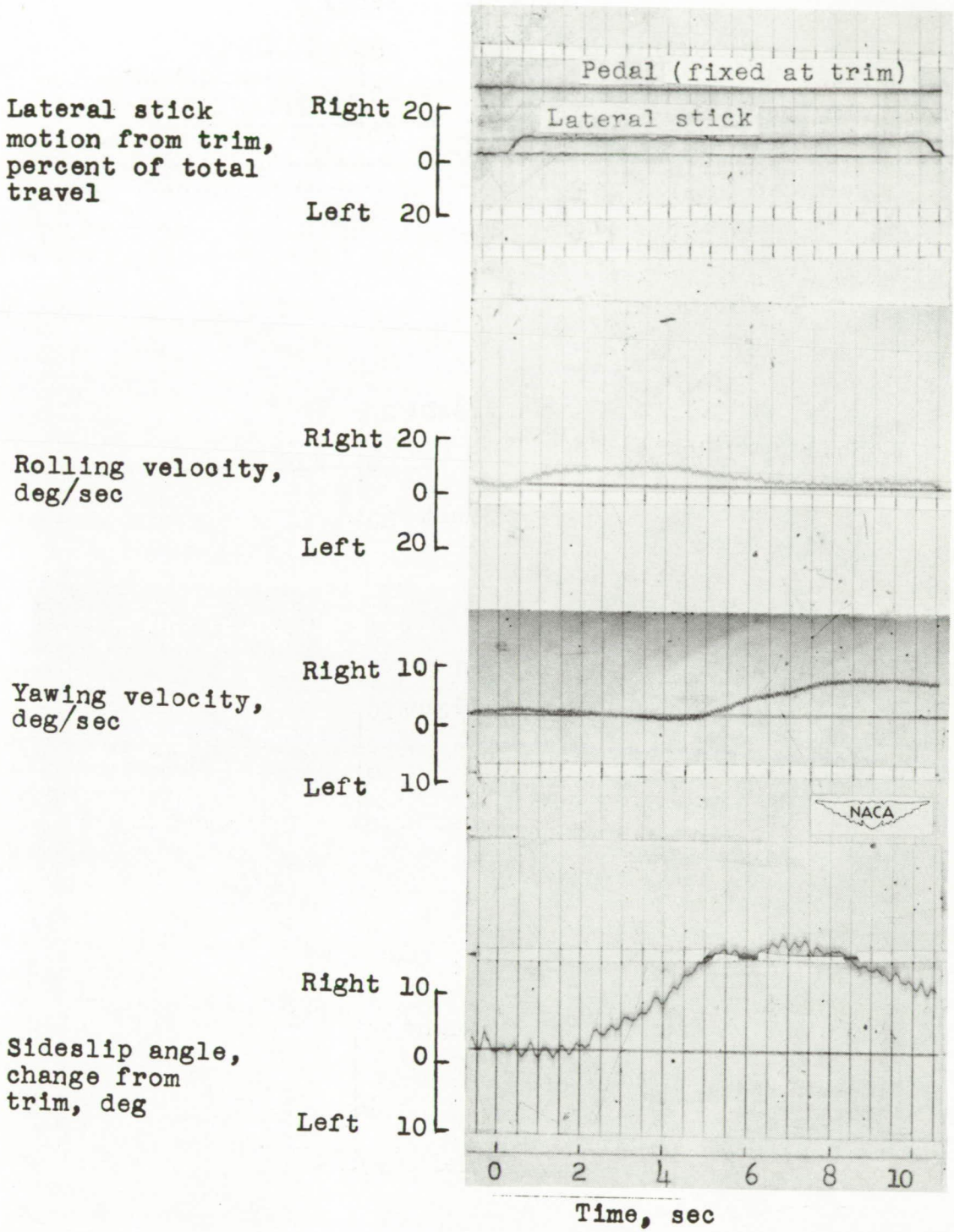
(c) Effective dihedral reduced 50 percent, theoretical.

Figure 10.- Continued.



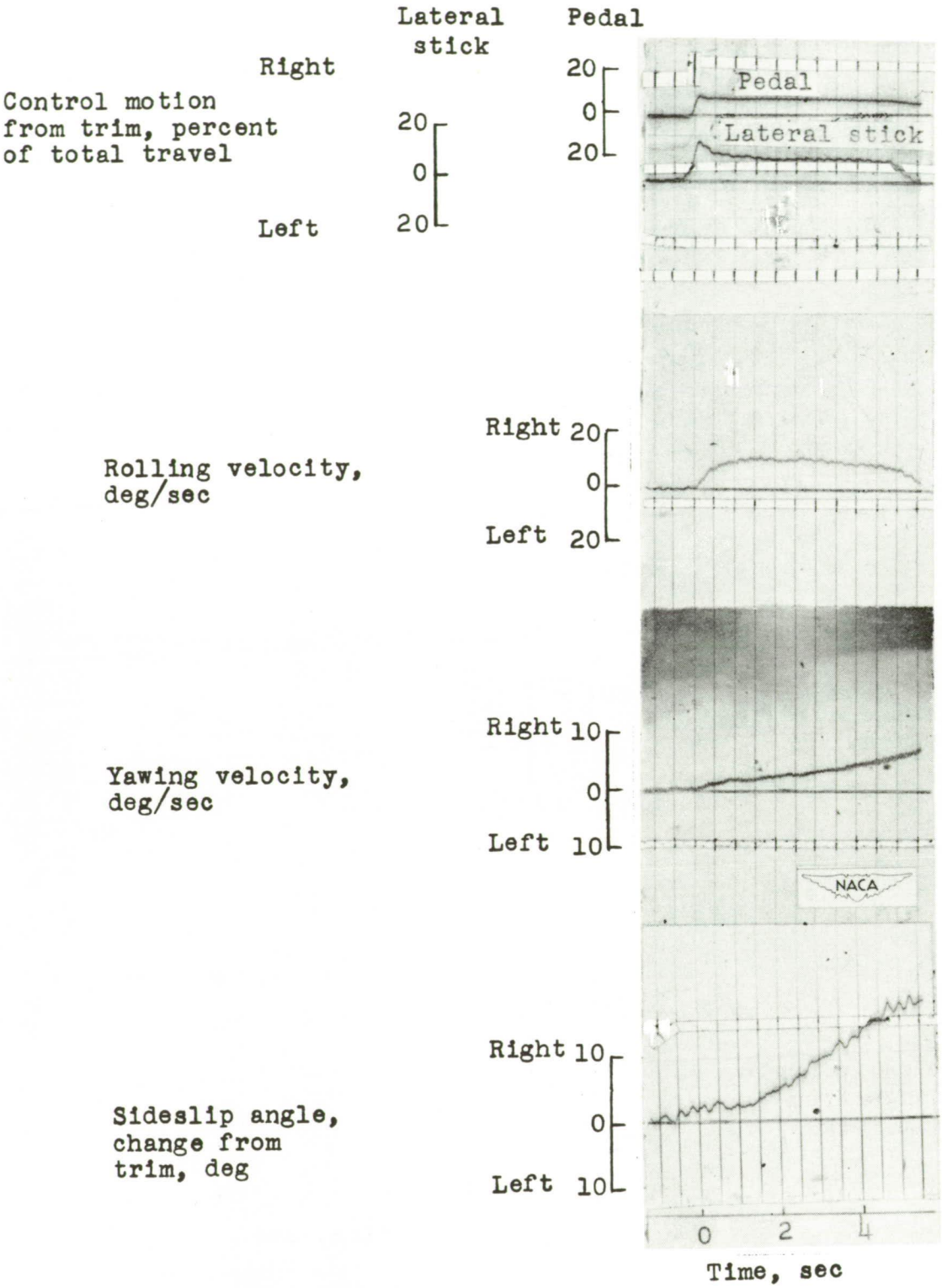
(d) Effective dihedral reduced 50 percent, experimental.

Figure 10.- Concluded.



(a) Pedals fixed.

Figure 11.- Experimental turn maneuvers for test helicopter at approximately 80 knots; power one-half that for level flight; large plywood wings attached.



(b) Pedals moved with stick to simulate change in control rigging.

Figure 11.- Concluded.

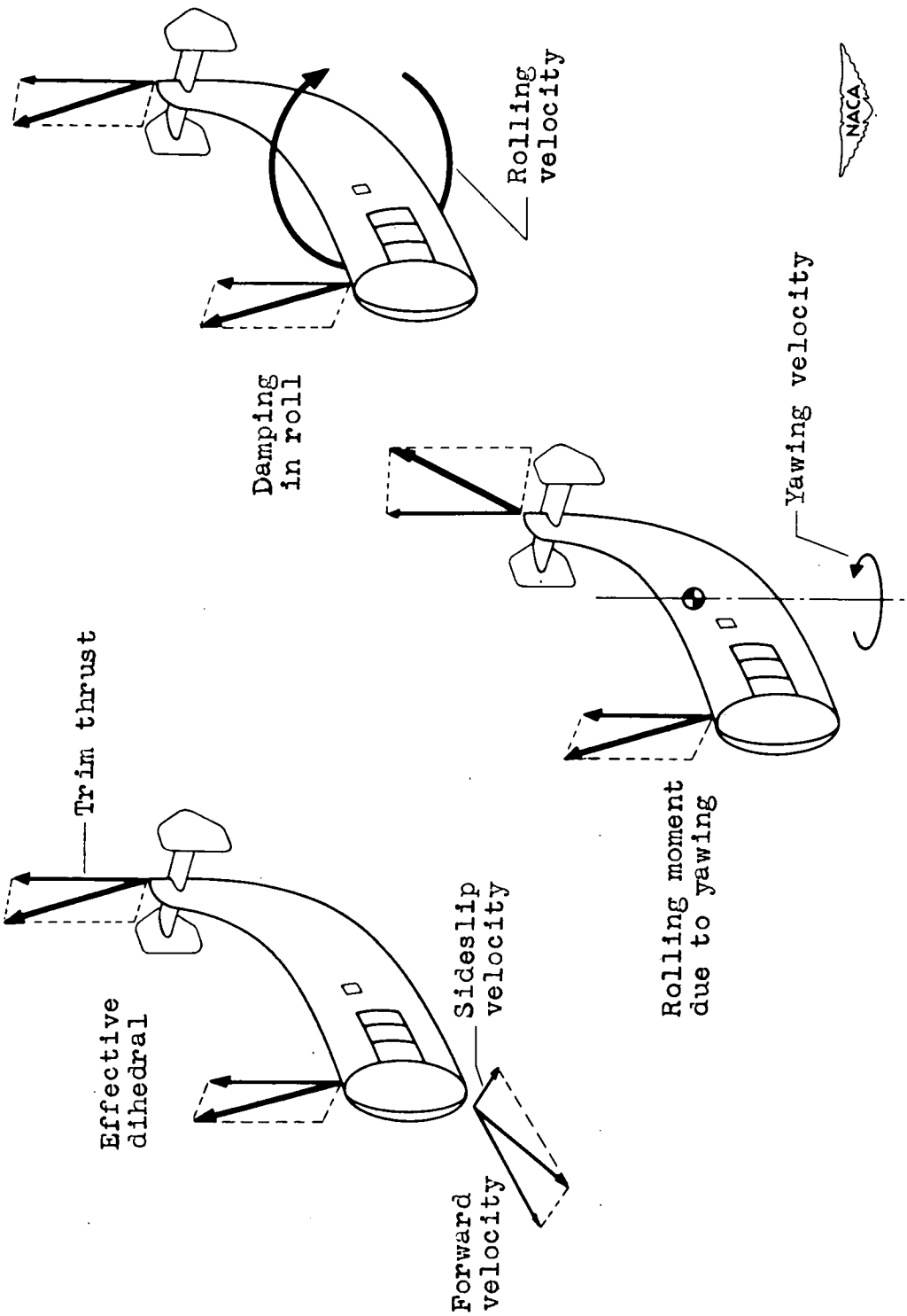


Figure 12.- An explanation of the source of effective dihedral, damping in in roll, and roll due to yawing for tandem helicopter.

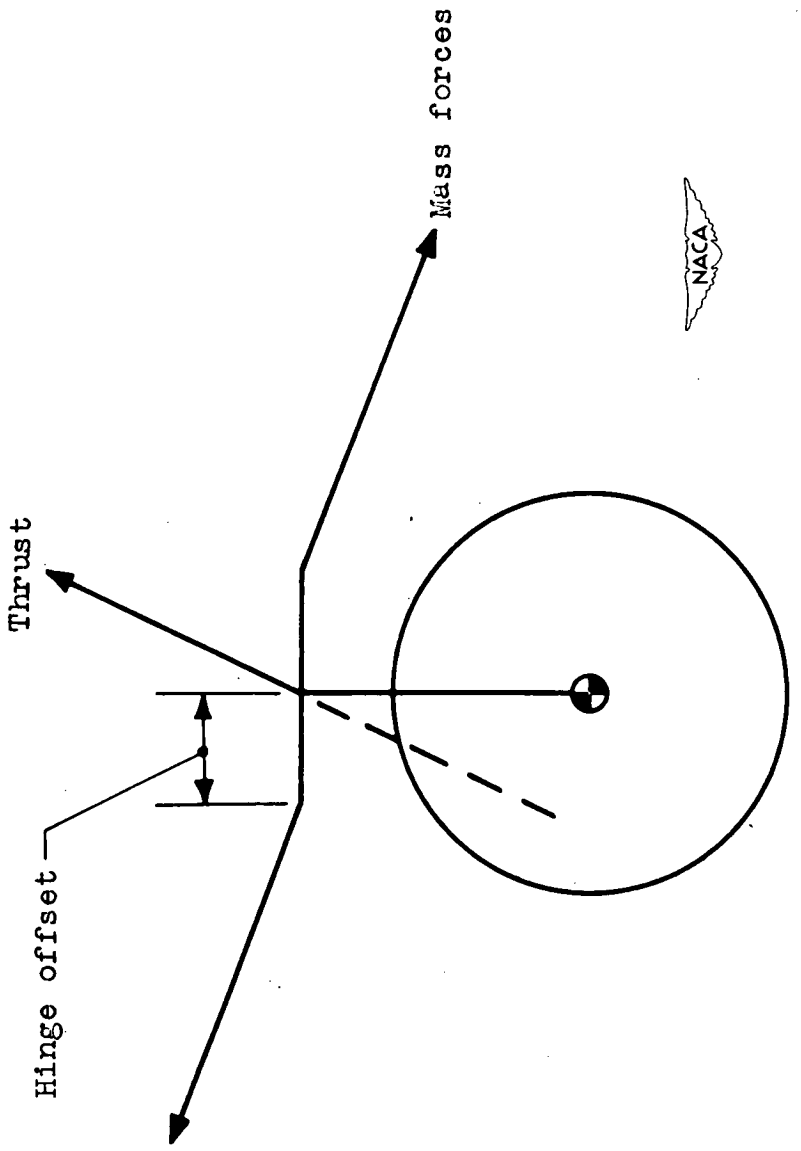


Figure 13.- Effect of offset flapping hinges on rolling moment due to a lateral rotor tilt.